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Aluminum Critical Mineral Production Feasibility via Landfill Mining: Preliminary study of potential project locations and co-benefits

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ALUMINUM CRITICAL MINERAL PRODUCTION FEASIBILITY VIA LANDFILL MINING: PRELIMINARY STUDY OF POTENTIAL PROJECT LOCATIONS AND CO-BENEFITS

By

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List of Abbreviations

USGS = United States Geological Survey

US = United States

PFC = Perfluorocarbon

CO_2 = Carbon dioxide

Mt = Million Metric tons

IAI = International Aluminum Institute

EPA = Environmental Protection Agency

MSW = Municipal solid waste

LFMR = Landfill Mining and Reclamation

ELFM = Enhanced Landfill Mining

LCA = Life Cycle Assessment

TEA = Tecno-economic Assessment

UBC = Used Beverage Can

LMOP = Landfill Methane Outreach Program

LFG = Landfill gas

TCEQ = Texas Commission on Environmental Quality

FEMA = Federal Emergency Management Agency

Abstract

In 2022, aluminum was named a critical mineral by the United States Geological Survey (USGS) and the global demand for aluminum is projected to increase by 40% from 2020 to 2030 (Aleksić 2023). There are currently no large-scale bauxite mines in the United States to contribute to aluminum production, and this study aims to investigate the feasibility of aluminum landfill mining in the United States to produce secondary aluminum. The feasibility of landfill mining for the purpose of recovering materials and energy is a relatively new technology, and often co-benefits are required to make these projects economically viable. Publicly available databases of national and statewide landfills are utilized, and their aluminum content is estimated. The use of ArcGIS as a mapping and analysis tool for the Houston, Texas area is also part of this study.

1 Introduction

Aluminum is a widely used mineral in both commercial and industrial settings due to its electrical conductivity, light weight, malleability, and thermal properties. The strength and durability of aluminum lend to its utilization in construction such as siding, roofs, or window and door frames. Application of aluminum in transportation systems to improve fuel efficiency has become increasingly common due to its light weight and durability. The electrical conductivity of aluminum allows for its use in long distance electrical transmission. The thermal properties of aluminum also make its use in heat exchange systems beneficial. The malleability and durability of aluminum makes its use as a packaging material for consumer goods common. (OECD 2012)

Due to the prolific use of aluminum, the United States Geological Survey (USGS) named aluminum as one of the 50 critical minerals in their 2022 report. A critical mineral is defined by the Energy Act of 2020 as “a non-fuel mineral or mineral material essential to the economic or national security of the United States and which has a supply chain vulnerable to disruption” (USGS 2022). Aluminum is a commodity used in all sectors of the United States (US) economy making the availability and accessibility of aluminum to the US vital. The current and future flows of US aluminum production, consumption, and disposal must be evaluated. New technologies should be explored to ensure mineral access and independence for the nation.

1.1 Aluminum Production and Disposal in the US

The production of primary aluminum requires the mining of bauxite, which is chemically processed into alumina, followed by the electrolysis of the alumina to produce aluminum (Figure 1.1). At present, there are no large-scale bauxite mines in the US to contribute to primary aluminum production, though the US imports bauxite and completes the aluminum production process (OECD 2012). The production of primary aluminum does result in undesirable and environmentally impactful waste products such as air emissions including perfluorocarbon (PFC) gasses and carbon dioxide (CO_2). Electricity or energy use and anode production for the electrolysis of alumina are the main contributions to these emissions. The greatest waste product from the bauxite to alumina processing step is “red mud”, an alkaline residue with a highly complex composition that is dependent on the composition of the bauxite ore. Red mud has historically been disposed of in oceans or lined waste containment sites. Recycling and reuse methodologies for red mud have not been explored or implemented at scales great enough to match its production. The production of primary aluminum has led to the production and accumulation of the hazardous byproduct red mud to persist in the environment (Menzie 2010).

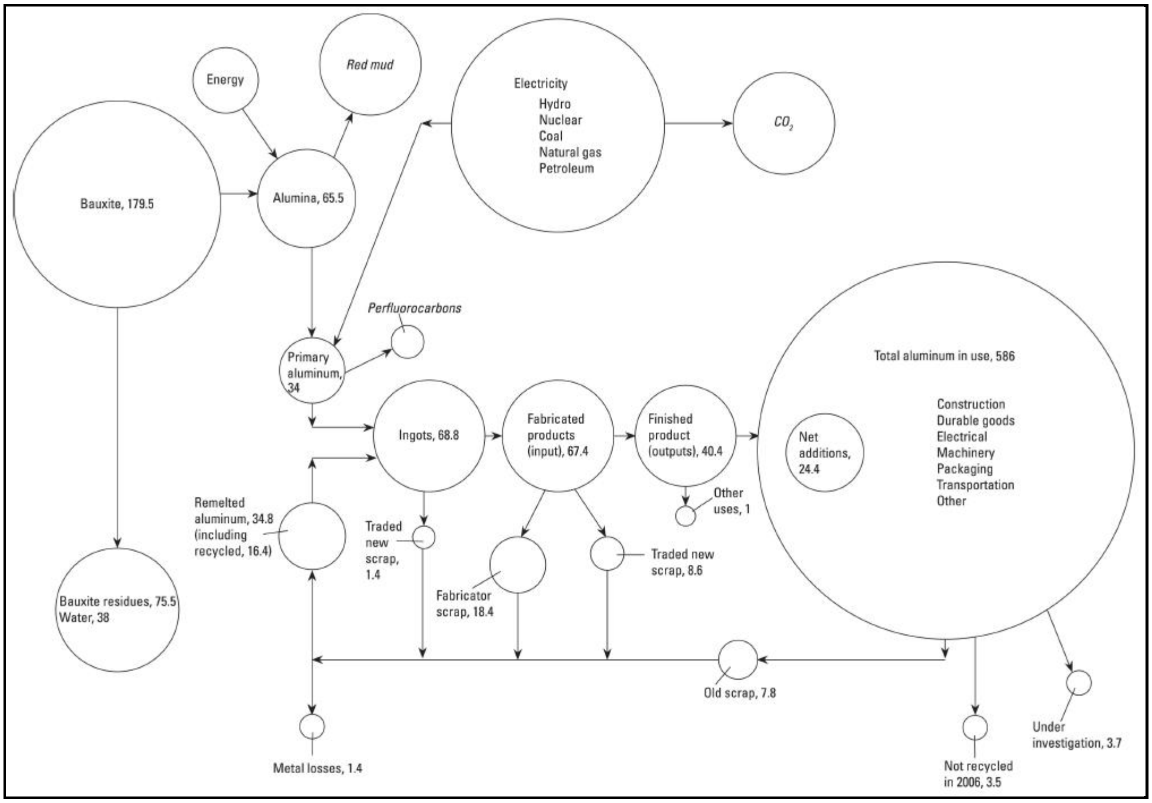

Figure 1.1. Global flow of aluminum in 2006. Units of million metric tons (Mt) with emissions in italics, and size of circles scaled to relative weight or emissions. (Martchek 2007)

In 2006, the global production of primary aluminum is estimated to be 34 million metric tons (Mt), where bauxite is processed to alumina, and the smelting of the alumina produces aluminum. Global secondary aluminum, or aluminum recovered as new scrap from the production process or recycled post-consumer scrap, is estimated to have totaled 11.8 Mt in the same year. The total global aluminum production in 2006 was approximately 45.9 Mt, with the US contributing 2.28 Mt and 3.54 Mt for primary and secondary aluminum, respectively. In 2006, 3.5 Mt of aluminum was not recycled and likely disposed of in landfills or incinerated (Menzie 2010).

More recently available data shows global aluminum production has been continuing to increase since 2006 (Figure 1.2). By 2021, the total production of aluminum globally reached 106.897 Mt, where 67.092 Mt was primary aluminum and 35.848 Mt was secondary, or recycled, aluminum. In the same year, it is estimated that the weight of aluminum landfilled or incinerated was 7.319 Mt (IAI 2023). Primary aluminum production remains the dominant source of global aluminum from 2006 to 2021.

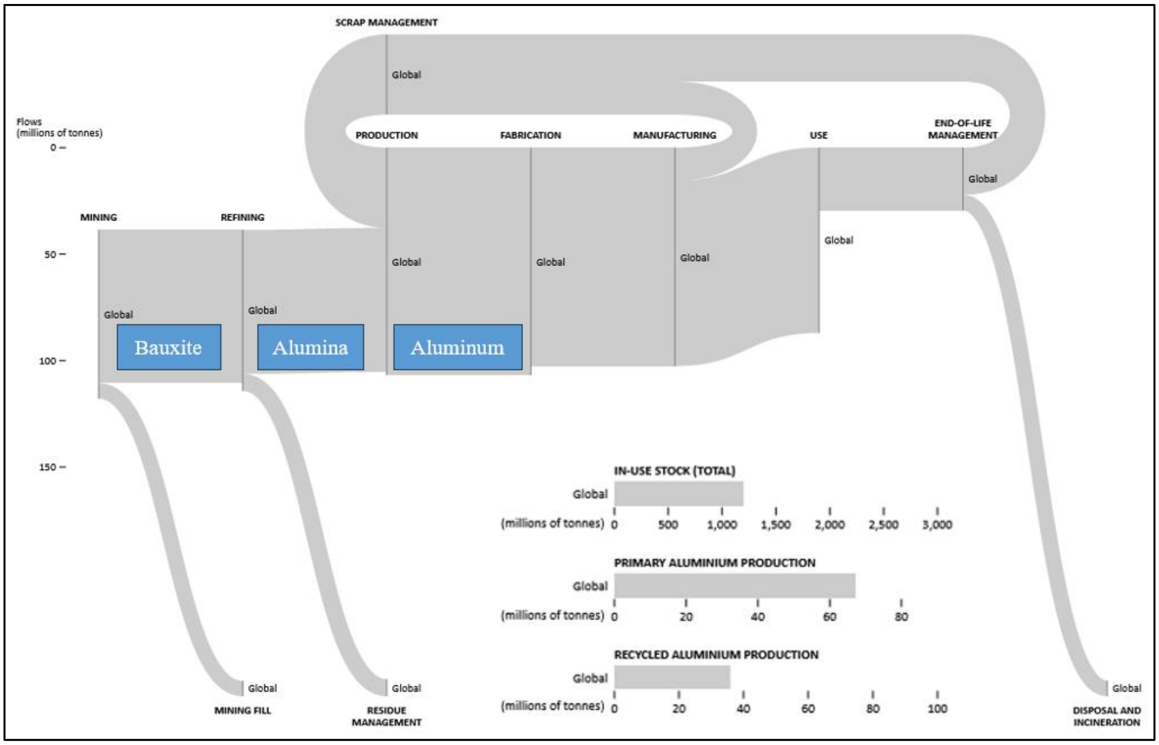

Figure 1.2. Global flow of aluminum in 2021. Primary aluminum production is estimated to be 67.092 Mt and secondary aluminum production is estimated to be 35.848 Mt, bringing the total global aluminum production to be approximately 106.897 Mt in 2021. The weight of aluminum landfilled is estimated to be 7.319 Mt in the same year. (IAI 2023)

The estimated global demand for aluminum is expected to continue the same trend observed from 2006 to 2021, with expected growth in industrial sectors, such as transportation, construction, packaging, and electrical driving the increasing demand (Aleksić 2023). The International Aluminum Institute (IAI) projects a 40% increase in demand over the current decade, and by 2050 the global production of aluminum could reach 176.395 Mt to meet these demands (Figure 1.3). The environmental implications of mining bauxite and the following processing and smelting operations required in primary aluminum production are reflected in the IAI estimated breakdown of future aluminum production. By 2050, the IAI predicts most of the global aluminum to be derived from secondary production, or approximately 90.367 Mt, as compared to 81.498 Mt as primary aluminum production. In the same year, the IAI estimates 18.082 Mt of aluminum to be disposed of or incinerated, indicating an imperfect recycling process in all waste handling facilities.

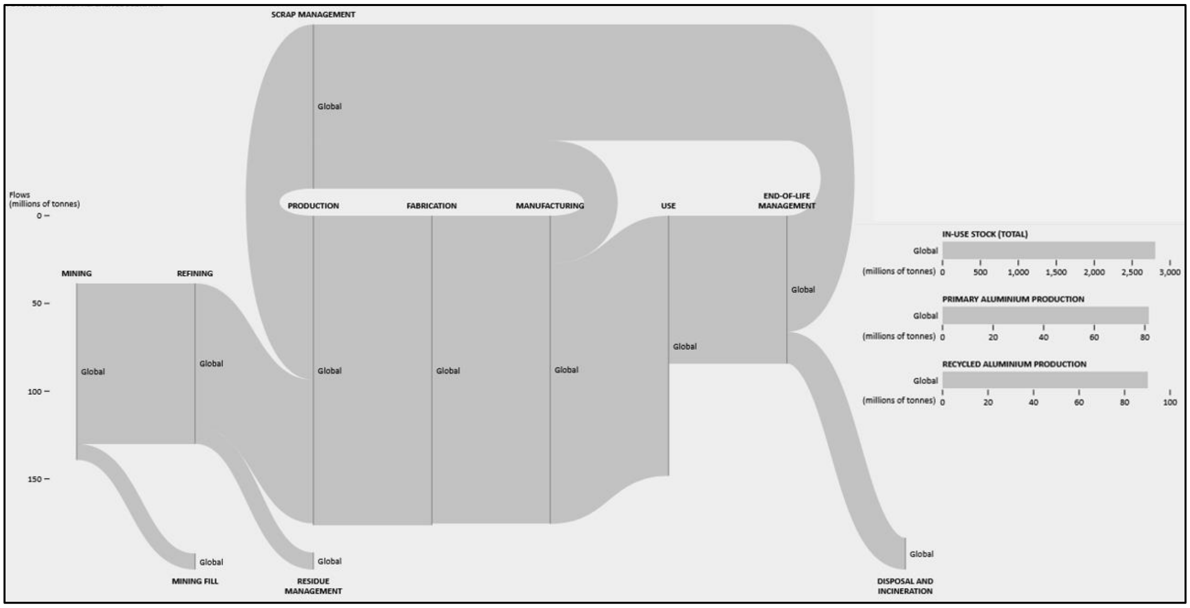

Figure 1.3. Projected global aluminum flow in 2050. Primary aluminum production estimated to be 81.498 Mt and secondary aluminum production estimated to be 90.367 Mt, making the total projected global aluminum production approximately 176.395 Mt in 2050. The weight of aluminum disposed or incinerated is estimated to be 18.082 Mt in the same year. (IAI 2023)

Of interest in this study, the aluminum production and disposal for North America is summarized by the IAI with the most recently available data for 2021 in Figure 1.4. As mentioned previously, the US and the North American region, do not have any of its own large-scale, commercially viable bauxite mines. Therefore, any of the primary aluminum produced in this region relies on the import of bauxite from other regions (OECD 2012). This is reflected in the flow of aluminum for the region, where 3.880 Mt produced is primary aluminum, and 5.451 Mt is secondary, or recycled, aluminum. In 2021, it is estimated that the North American region disposed of or incinerated 2.923 Mt of aluminum (IAI 2023). This fraction of potentially disposed aluminum in the region is valuable in this study in quantifying and determining the feasibility of recovering and recycling this pool of aluminum.

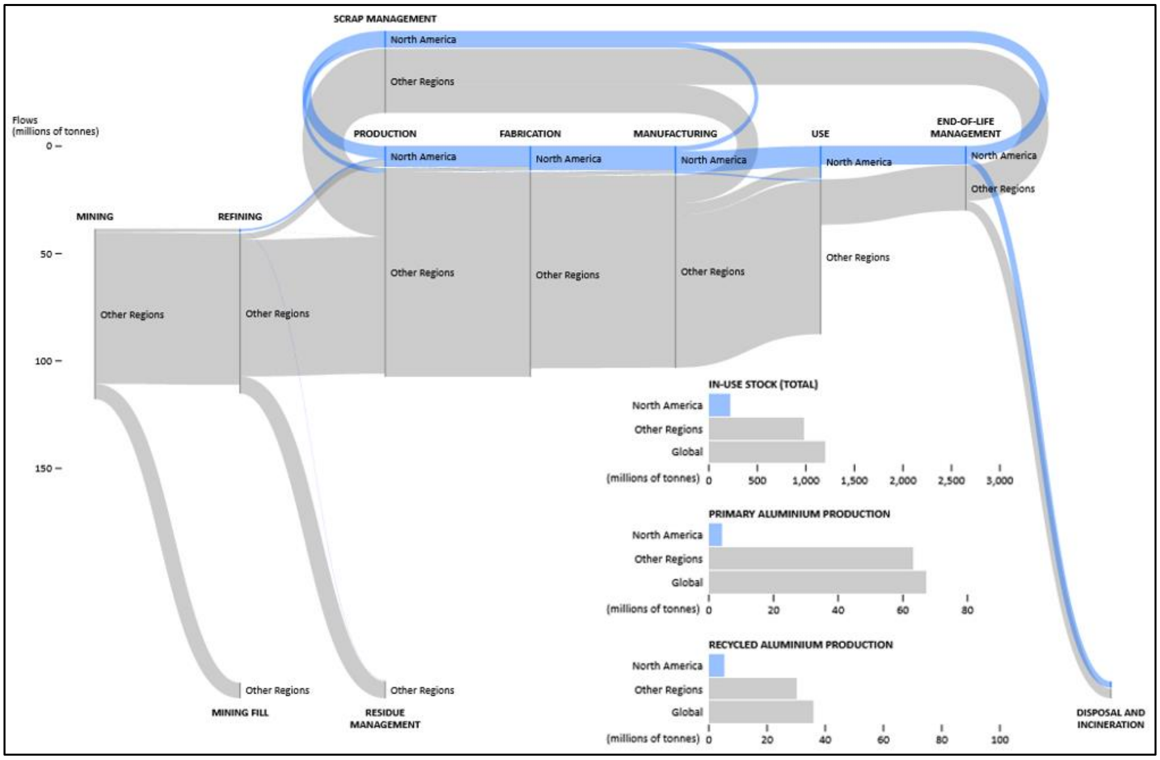

Figure 1.4. North American flow of aluminum in 2021. Primary aluminum production is estimated to be 3.880 Mt and secondary aluminum production is estimated to be 5.451 Mt, bringing the total aluminum production for the region to be approximately 9.673 Mt in 2021. The weight of aluminum landfilled is estimated to be 2.923 Mt in the same year. (IAI 2023)

The US EPA has kept a record from 1960 to 2018 summarizing the weight of landfilled materials and their relative percentage of the total weight of landfilled municipal solid waste (MSW) (Table A.1). The portion of US EPA data quantifying the amount of aluminum and other potentially valuable metals against all MSW is summarized in Table 1.1. It is estimated by the US EPA that 16.69 Mt of aluminum was disposed of in US landfills from 1960 to 2018 (US EPA 2020). The relative percentage of aluminum being landfilled in the MSW stream has generally increased since 1960. In 2018, aluminum accounted for 2.41 Mt, or 1.8%, of all MSW by weight. Ideally, the recovery of all types of ferrous and nonferrous metals would be achieved in a landfill mining project. Since 1960, the relative percentage by weight of MSW as recorded by the US EPA of ferrous and nonferrous metals has been between 7.2% and 13%, representing a significant fraction of MSW by weight, though likely a much smaller relative contribution by volume. Of the total landfilled aluminum, a breakdown of various aluminum products landfilled in million metric tons can be seen in Figure 1.2 from 1960 to 2000. The aluminum containing products landfilled at the greatest rate are passenger cars and metal cans.

Table 1.1. Metals Landfilled in the Municipal Waste Stream from 1960 to 2018. Landfilling after recycling, composting, other food management pathways and combustion with energy recovery. Does not include construction & demolition debris, industrial process wastes or certain other wastes. Percentage by weight of total landfilled material. Full table available in the Appendix. (US EPA 2020)

Material		Million Metric Tons, Mt									
Metals		1960	1970	1980	1990	2000	2005	2010	2015	2017	2018
	Ferrous	9.30	11.02	10.89	7.91	7.13	7.76	8.45	9.04	9.46	9.55
	Aluminum	0.31	0.72	1.26	1.36	1.76	2.02	2.17	2.26	2.42	2.41
	Other Nonferrous	0.16	0.32	0.54	0.28	0.44	0.48	0.47	0.60	0.66	0.67
Total Metals		9.77	12.06	12.69	9.55	9.33	10.26	11.09	11.90	12.55	12.64
Material		Percent of Total Landfilled									
Metals		1960	1970	1980	1990	2000	2005	2010	2015	2017	2018
	Ferrous	12.4%	10.8%	8.9%	6.0%	5.6%	6.0%	6.8%	7.2%	7.4%	7.2%
	Aluminum	0.4%	0.7%	1.0%	1.0%	1.4%	1.6%	1.8%	1.8%	1.9%	1.8%
	Other Nonferrous	0.2%	0.3%	0.4%	0.2%	0.3%	0.3%	0.4%	0.5%	0.5%	0.5%
Total Metals		13.0%	11.8%	10.3%	7.2%	7.3%	7.9%	9.0%	9.5%	9.8%	9.5%

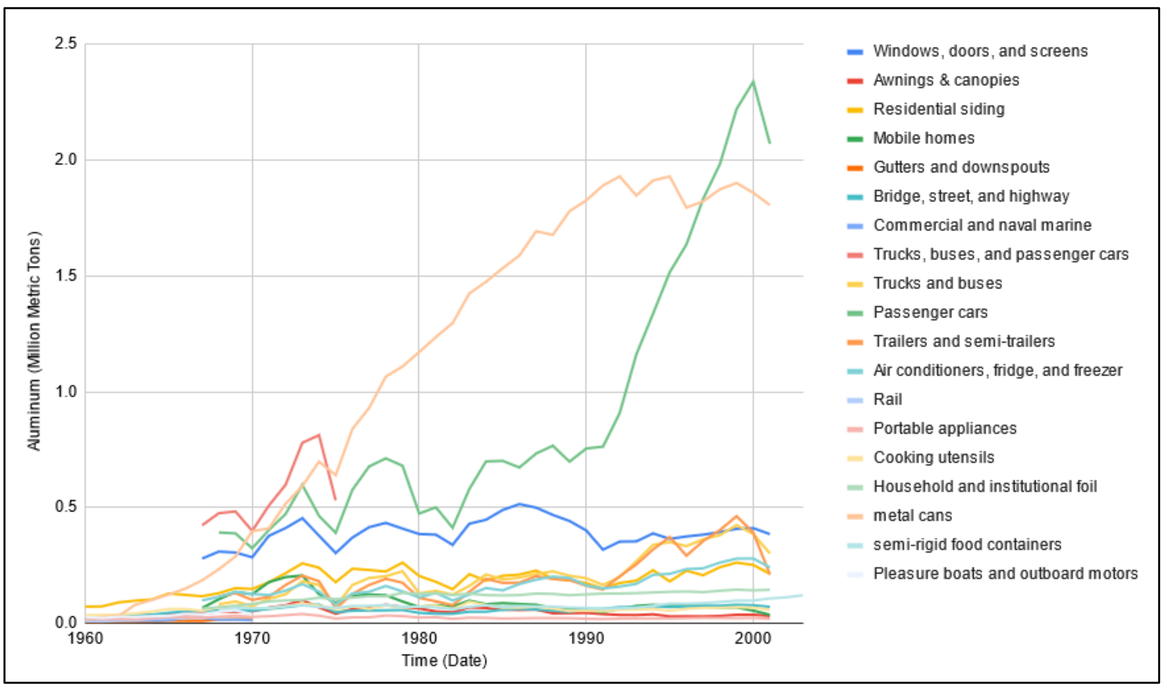

Figure 1.5. Estimate of Historical Aluminum Landfilling by Product. Passenger cars shown as the green line, and metal cans shown as the light orange line, are the two aluminum containing products landfilled at the greatest rates. (Garnio 2014)

The weight of metal cans that have been landfilled in the US from 1990 to 2000 has exceeded 1.75 Mt each year during that decade. The industry recycling rate of aluminum cans through this period has remained relatively constant between 60-70% (Figure 1.6A). The industry recycling rate includes new scrap during the production of aluminum cans, as well as imports of used beverage cans to the US. From 2000 to 2010, the industry recycling rate dropped below 60% before increasing once again and reaching 63.6% in 2018. An industry recycling rate of 100% has not historically been achieved, and therefore it can be assumed that some aluminum cans are landfilled rather than being recycled. The number of aluminum cans that have been recycled since 1972 has also been documented and reflects the same pattern as the recycling rate during the same period (Figure 1.6B). In 2018, 56.2 billion aluminum cans were recycled and since the beginning of tracking in 1972 the aluminum industry has recycled over 2 trillion cans.

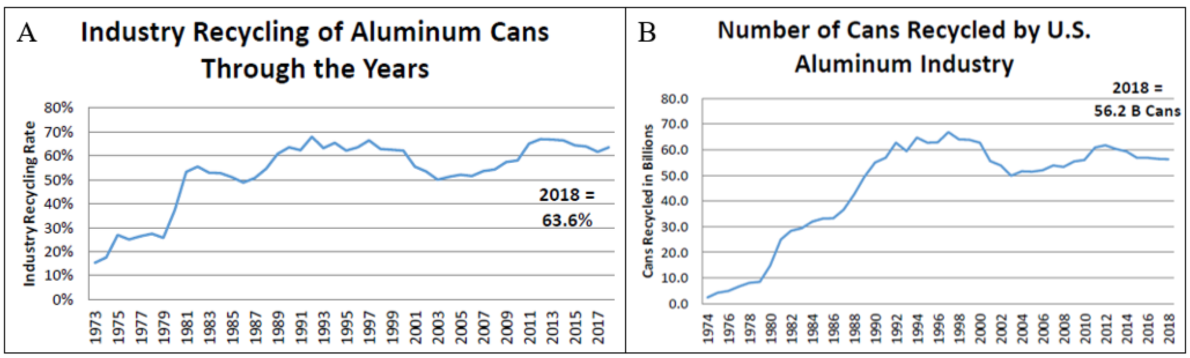

Figure 1.6. US Aluminum Can Recycling. (A) US Aluminum Can Recycling Rate from 1973 to 2018. (B) Number of aluminum cans recycled from 1972 to 2018. (The Aluminum Association 2019)

To more specifically focus on post-consumer used beverage can (UBC) recycling statistics, Figure 1.7 represents the flow of aluminum UBCs in the US with the most recently available data from 2019. As expected, the recycling rate estimated for this year is 41.8%, or 0.521 Mt (IAI 2023), which is less than the industry recycling rates discussed previously that include new scrap and imported UBCs. This study is more interested in the domestic, post-consumer aluminum UBCs and an estimate of their disposal and quantity in US landfills. The rate of estimated landfilled aluminum UBCs in 2019 from Figure 1.7 is 46.1%, or 0.574 Mt (IAI 2023). This significant disposal rate and total weight of aluminum UBCs support the viability of utilizing landfill mining to recycle this desirable resource.

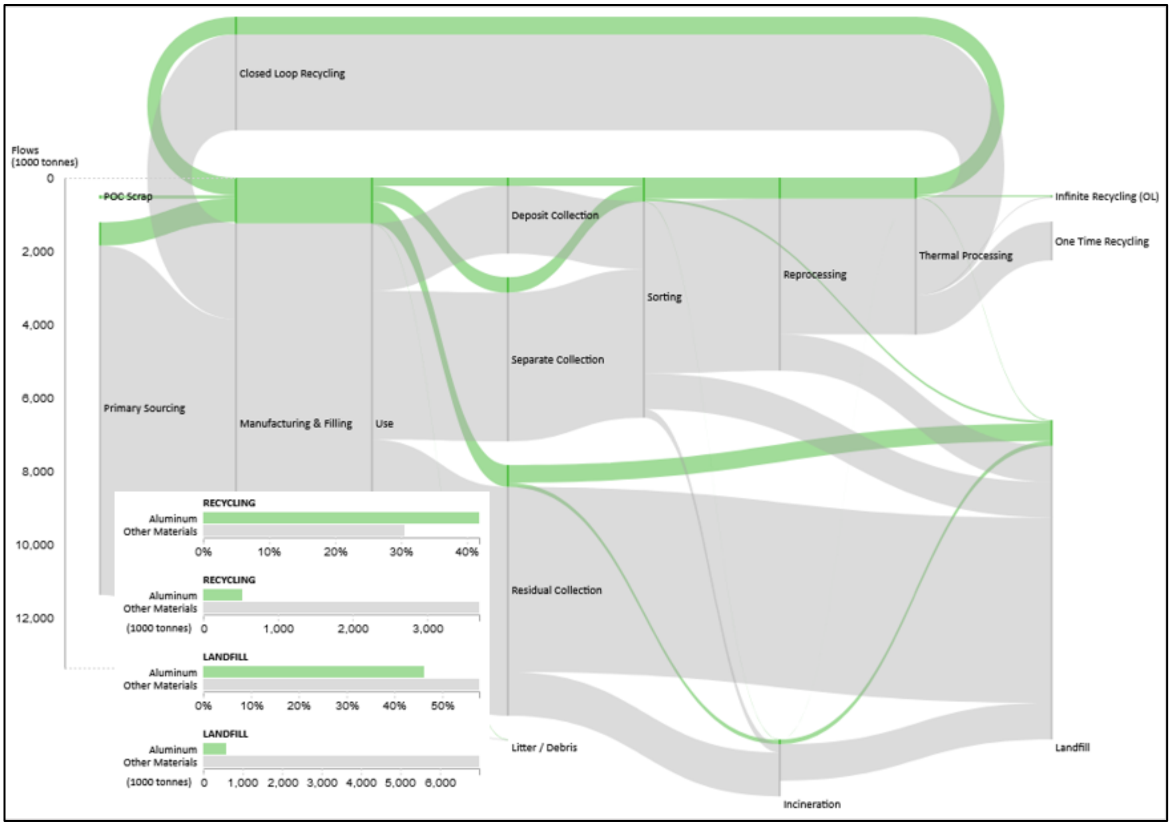

Figure 1.7. United States Aluminum Used Beverage Can Flow in 2019. In 2019, it is estimated that 41.8%, or 0.521 Mt, of aluminum used beverage cans were recycled, and 46.1%, or 0.574 Mt, were landfilled. (IAI 2023)

The trend of landfilled aluminum cans from 1972 to 2020 can be seen in Figure 1.8. Considering the previously reviewed data of various aluminum products that are landfilled, it is expected that aluminum UBCs will be the most viable and abundant type of aluminum by weight in MSW landfills. Further analysis with statewide aluminum UBC recycling rates will be utilized in this study to determine regions where landfill mining feasibility may be improved due to greater estimated of landfilled aluminum UBCs.

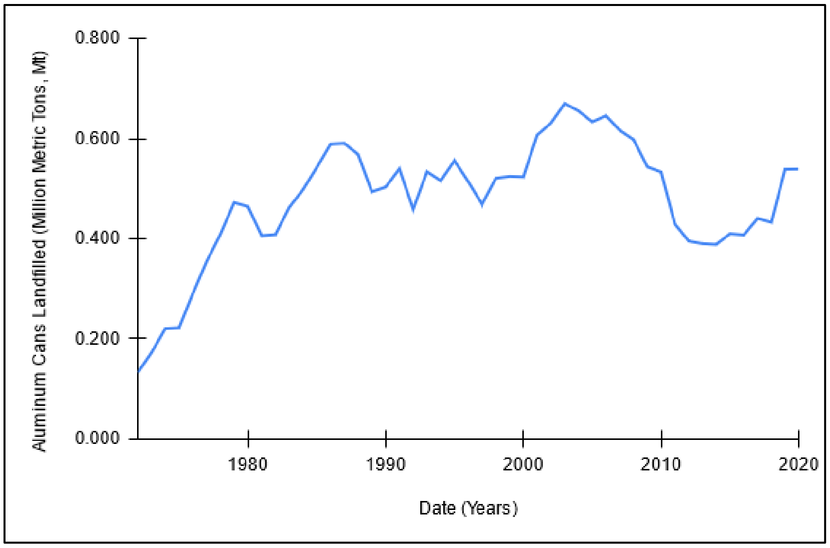

Figure 1.8. Weight of Aluminum Cans being landfilled in the US from 1972 to 2020 (Aluminum Statistical Review 2021).

1.2 Landfill Mining History and Current Regulations

The process of landfill mining and reclamation (LFMR) is utilized to excavate and process previously landfilled solid wastes. The first documentation of LFMR is in 1953 in Tel Aviv, Israel at a city owned and operated landfill. The purpose of this LFMR project was to recover soil utilizing conveyors and a rotating trommel screen to separate the materials excavated from the landfill. This project in Tel Aviv is the only LFMR scenario documented in literature until the 1980s (US EPA 1997). Since this project, a majority of the LFMR projects documented in the literature have sought to reclaim soil as in Tel Aviv, but other objectives have included airspace reclamation in open landfill sites, landfill expansion, land redevelopment, improved landfill liner technology, reducing greenhouse gas emissions, or using reclaimed materials as combustibles for energy generation. The soil reclamation alone in an LFMR project provides soil to cover other active portions at a landfill site without excessive transportation costs associated with trucking soil from greater distances. The greatest economic benefit is often the regained landfill airspace, buying the landfill organization more time to accept waste (Wang 2018).

A more recent term adapted to describe landfill mining with the purpose of excavating landfilled waste streams to utilize materials and energy with strict environmental and social criteria, is enhanced landfill mining (ELFM). The main difference between LFMR and ELFM is the material recycling, utilization of energy sources, and restoration of landscapes prioritized in ELFM. An important factor in the ELFM approach is valuing all excavated waste and energy instead of focusing on only a few materials to recover (Jones 2013).

The greatest barrier for many LFMR and ELFM projects is their economic viability. Recovering materials or minerals from landfilled waste is not often beneficial enough on its own to warrant landfill mining. For a landfill mining project to be economically viable, co-benefits in addition to resource recovery are usually required for a community or organization to buy in (Wang 2018). Co-benefits to a landfill mining project may be unique, depending on the landfilled waste and if it is uniform and known, or hazardous. It can be speculated that as natural resources become scarcer in the future, the demand for landfill mining will increase to reuse and recycle those resources. Currently, there is additional funding and support in Europe to encourage and facilitate the costs of landfill mining, but without the same incentives at present in the US, the addition of co-benefits to material recovery in landfill mining projects are likely necessary.

The permitting process for a landfill mining project in the US is currently new. Many states do not explicitly describe resource recovery in landfill mining permits, though some provide environmental guidelines and regulations. Some permits focus purely on soil reclamation in terms of landfill mining, and landfill mining as a term is rarely used. An example of a state with landfill mining outlined in their administrative code is Texas, which provides a specific landfill mining permit to apply for (TCEQ 2024a).

1.3 Scope and Objectives

The naming of aluminum as a US critical mineral in 2022 (USGS 2022) and the projected demand of aluminum products to increase by nearly 40% from 2020 to 2030 makes aluminum an increasingly desirable mineral. In this project, the data tracking the recycling rates of aluminum products along with the historical landfilling rates of aluminum will build a case for the resource recovery of aluminum through landfill mining projects. Estimations for aluminum in landfills will be completed for regions identified as potentially having the greatest concentrations of aluminum in their waste. Case studies of interest that lie within the areas recognized as potential landfill mining sites will also be reviewed to assist in the identification of co-benefits. The scope of this study is to identify potential landfill mining sites across the US by building databases and identifying potential co-benefits for the regions or sites identified.

Additionally, the use of the mapping and analysis software ArcGIS Pro to visualize landfill locations and their current use or condition through satellite imagery will be completed for areas of interest. FEMA flood hazard maps are utilized in ArcGIS to compare landfill proximity to areas of flood risk. These ArcGIS analyses were first completed at a smaller scale across the greater Houston area, and finally expanded to include the entire US.

The work completed in this study will contribute to greater project objectives by providing leads to areas of interest for landfill mining projects that will specifically seek to recover aluminum. The identification of co-benefits through literature review of previous proposed or completed case studies will offer insight to greater Life Cycle Assessment (LCA) and Tecno-economic Assessments (TEA) that will hopefully justify both the environmental and economic benefits of landfill mining. These aspects of potential landfill mining projects can contribute to the social science approach that is prioritized in the greater DOE project objectives, where co-benefits for both the economic feasibility of landfill mining as well as environmental and community benefits can be explored based on regional site selection.

2 Landfill Mining Feasibility Site Selection

2.1 Landfill Database Acquisition and Analysis

This study will consider multiple criteria in terms of the feasibility of a landfill mining project taking place at a given landfill. First, estimations of landfilled aluminum must be made based on US EPA values for the fraction of landfilled MSW that is aluminum (US EPA 2020). Other considerations in this study include the presence of a bottle bill in each state which was assumed to correlate with the rate of aluminum cans being landfilled (Waste360 2023). Results of this initial analysis will allow for a subset of states to be selected. Utilizing the Landfill Methane Outreach Program (LMOP) landfill and project database compiled by the US EPA (US EPA 2024), the states of interest identified previously can be chosen from this database for further estimations of aluminum content in their landfills and specific landfill sites, state counties, or landfill owner organizations can be sorted and ranked by their potential for landfill mining projects to occur.

Texas was found to be the most promising state in the US in terms of hosting a landfill mining project with a large population and a low recycling rate of aluminum UBCs leading to a large quantity of landfilled aluminum UBCs. Quantitative estimations of landfilled aluminum quantities, the lack of landfill mining restriction and a current permit for landfill mining activities (TCEQ 2024a), and an identified landfill mining project currently being pursued (Houston One Voice 2022) all increase the viability of landfill mining projects in the state. This current landfill mining project proposed to take place at the Ruffino Hills landfill will be reviewed in more detail in Section 2.2 of this study. The Texas Commission on Environmental Quality (TCEQ) records their own historical database of permitted MSW landfill facilities that are active, inactive, or pending permits, closed landfills, and closed and unnumbered MSW facilities that operated prior to permit requirements (TCEQ 2024b). The US EPA LMOP database was compared to the collection of databases recorded by the TCEQ for the Houston area to evaluate the completeness of the US EPA LMOP database, and this dataset (Appendix A.4) was utilized in further analysis during this study.

2.1.1 Quantifying Landfilled Aluminum

As discussed previously, the rate of aluminum UBC recycling has not been 100% (Figure 1.6A), and therefore it was assumed for the purposes of this study that most of the non-recycled aluminum cans are being landfilled. The estimated weight of landfilled aluminum UBCs in the US over the past 50 years can be reviewed in Figure 1.7, with 0.433 Mt of aluminum UBCs being landfilled in 2018 alone (Aluminum Statistical Review 2021). The US EPA estimated 2.41 Mt of total aluminum landfilled in the same year (US EPA 2020), and therefore it can be estimated that approximately 18% of landfilled aluminum in 2018 was in the form of UBCs. This percentage is significant enough to justify the use of statewide UBC disposal data to determine which states would be most viable for landfill mining in terms of aluminum UBC content in their landfills.

Statewide aluminum can recycling rates and the total weight of landfilled aluminum (Waste360 2023) have been calculated and summarized for a select number of states in Table 2.1. The values for all US states can be found in their entirety in Appendix A.2. For the purposes of this study, this data was sorted in descending order according to the states having the greatest weight of landfilled aluminum. According to this data, Texas, Florida, Illinois, Georgia, Ohio, and California have the greatest potential weight of aluminum as UBCs in their landfills.

Table 2.1. States with the Greatest Total Estimated Landfilled Aluminum Cans (Waste360 2023).

State	Al Can Recycling Rate (%)	Al Can Deposit	Year Bottle Bill was passed	Al kgs/ capita generated	Al kgs/ capita disposed	Al kgs/ capita recycled	Population (April 2020-July 2021)	Al disposed (Thousands of Metric Tons)
Texas	16	No		4.40	3.72	0.68	29,527,941	109.83
Florida	25	No		5.67	4.26	1.41	21,781,128	92.87
Illinois	24	No		4.85	3.67	1.18	12,671,469	46.56
Georgia	20	No		4.40	3.54	0.86	10,799,566	38.21
Ohio	16	No		3.81	3.22	0.59	11,780,017	37.94
California	78	Yes (CRV, 5c)	1987	3.63	0.82	2.81	39,237,836	32.04

2.1.2 Statewide Landfill Site Data Sorting and Analysis

The Landfill Methane Outreach Program (LMOP) landfill and project database compiled by the US EPA contains approximately 2,600 landfills across the US that are currently accepting MSW or have been closed in the past few decades. This database excludes industrial and hazardous waste landfills. This publicly available database was originally developed for identifying landfill gas (LFG) energy projects across the US along with landfills identified as potential candidates for utilization of the methane gas from the landfill as an energy source (US EPA 2024). At the time of this study, 482 LFG energy project sites exist, and 459 candidate sites are included by the US EPA. Landfill mining and LFG collection could not occur simultaneously due to the gas collection pipes and covers requiring undisturbed conditions. The US EPA LMOP database is still utilized because it is publicly available, national level data, and if the LFG energy project were to cease, a landfill mining project could take place next. This database is available for download on a state-by-state basis, and therefore the landfill site data for Texas, Florida, Illinois, Georgia, Ohio, and California are saved due to these states being previously identified for having the greatest potential for aluminum as UBCs in their landfills. Preliminary screening of each states database was completed by removing duplicate data entries occurring due to changes in permitting or LFG project status.

These LMOP state-by-state landfill site databases provide the landfill opening year, closure year, and the weight of the waste in place as of 2020 for open sites, or as of their closure year. This information along with the most recently available data of 1.8% relative fraction of landfilled waste in the US that is aluminum for 2018 (Table 1.1, US EPA 2020), was used to estimate the approximate relative weight of aluminum in each landfill. This nationwide simplification was applied for each landfill site for the purposes of this study for ease of calculation, though a more accurate approach of state or regional landfilling rates of aluminum could be utilized if the data is available. In addition, the LMOP database includes the landfill owner, the owner's organization type, and the county in which the landfill is located. These characteristics of each landfill are used to sort each state's database for the purpose of identifying potential LFMR project sites.

As an example, a sample of the LMOP database for Texas with the previously described characteristics sorted and color coded to corresponding relative amounts of aluminum can be seen in Table 2.2 below. The LMOP landfill sites in Harris, Dallas, and Denton counties are included in this summary table. Of all counties in Texas, Harris County potentially has the greatest weight of aluminum in its landfills estimated at 2.63 Mt. Republic Services Inc., a private organization, owns landfills across the state of Texas that could potentially contain the most aluminum, estimated at 5.10 Mt, as compared to other landfill owner organizations. The complete dataset for Texas, along with the datasets for Florida, Illinois, Georgia, Ohio, and California can be found in their entirety in Appendix A.3.

Table 2.2. Sample of Texas EPA LMOP Landfill Database Sorted by Relative Amount of Aluminum by County and by Organization. Color coordinated with orange indicating county sorting and green representing the landfill owner organization. Data for waste in place most recently from 2020.

Landfill Name	**City**	**County**	**Ownership Type**	**LF Owner Org.(s)**	**Year Open**	**Year Close**	**Waste in Place (Mt)**	**Relative Al. (Mt)**	**Sum of Relative Al. by County (Mt)**	**Sum of Relative Al. by Org. (Mt)**
Whispering Pines LF	Houston	Harris	Private	Republic Services, Inc.	1978	2044	9.30	0.167	2.63	5.10
McCarty Road LF	Houston	Harris	Private	Republic Services, Inc.	1972	2033	90.33	1.626	2.63	5.10
Atascocita RDF	Humble	Harris	Private	Waste Management, Inc.	1983	2041	35.42	0.638	2.63	4.95
Blue Bonnet LF	Houston	Harris	Private	Waste Management, Inc.	1979	1998	2.33	0.042	2.63	4.95
Bellfort Boulevard LF	Houston	Harris	Public	City of Houston, TX	1954	1970	8.83	0.159	2.63	0.16
McCommas Bluff LF	Dallas	Dallas	Public	City of Dallas, TX	1981	2053	50.21	0.904	1.87	0.90
Skyline LF	Ferris	Dallas	Private	Waste Management, Inc.	1950	2038	25.11	0.452	1.87	4.95
Charles M Hinton Jr Regional LF	Rowlett	Dallas	Public	City of Garland, TX	2002	2053	7.11	0.128	1.87	0.22

City of Garland Castle Drive LF	Garland	Dallas	Public	City of Garland, TX	1978	2003	5.00	0.090	1.87	0.22
Hutchins Landfill	Hutchins	Dallas	Private	Republic Services, Inc.	1978	1992	0.91	0.016	1.87	5.10
Trinity Oaks LF	Dallas	Dallas	Private	Republic Services, Inc.	1977	2003	6.20	0.112	1.87	5.10
City of Grand Prairie LF	Grand Prairie	Dallas	Public	City of Grand Prairie, TX	1978	2047	4.57	0.082	1.87	0.08
Hunter Ferrell LF	Irving	Dallas	Public	City of Irving	1982	2077	3.91	0.070	1.87	0.07
Laidlaw/ Wilmer LF	Wilmer	Dallas	Private	LF Owner of Laidlaw/Wilmer LF	1992	2001	0.62	0.011	1.87	0.01
DFW Recycling & Disposal Facility	Lewisville	Denton	Private	Waste Management, Inc.	1972	2023	64.99	1.170	1.62	4.95
Camelot Landfill	Lewisville	Denton	Public	City of Farmers Branch, TX	1980	2047	20.24	0.364	1.62	0.36
City of Denton LF	Denton	Denton	Public	City of Denton, TX	1985	2065	4.54	0.082	1.62	0.08
Lewisville Landfill	Lewisville	Denton	Private	Republic Services, Inc.	1986	2003	0.00	0.000	1.62	5.10

Waste Management Inc. is also a private ownership organization who potentially own 4.95 Mt of landfilled aluminum in the state of Texas (Table 2.2). The benefits and drawbacks of landfill mining in a private or publicly owned landfill are considered in this study. Large private organizations like Republic Services Inc. or Waste Management Inc. could be more difficult to work with regarding company guidelines or rules, though their estimated ownership of significant landfilled aluminum would make the possibility of multiple landfill mining projects company-wide very efficient in terms of resource extraction. Publicly owned landfills could be more accessible and open to landfill mining projects given economic, environmental, and community benefits. Email and phone interviews were attempted with minimal responses. At the time of this study, a clear distinction between private and publicly owned landfills for the purposes of landfill mining projects cannot be made.

There was a combination of open and closed landfills in the US EPA LMOP database, and therefore the projected runway amount of aluminum in currently active landfills was estimated for future landfill mining resource recovery feasibility. This estimation was a simplification and provides a linear extrapolation to the scheduled landfill closure year using the previous estimation of landfilled aluminum from the landfill's opening year to 2020. To limit the effects of the projected runway aluminum and provide a more accurate estimate, landfill closure years greater than the year 2050 are capped in 2050 for this estimation and are shown in red in Table 2.3 below. First, the linear waste rate was found [Equation 1], that does not account for population growth or changes in landfilling rates. The waste rate that was calculated was then multiplied by the number of years until the predicted closure of the landfill, added to the waste in place value, and multiplied by 1.8% to determine an estimate for the projected runway of aluminum that could be landfilled until the closure of each landfill site. This calculation was done for each active landfill in the LMOP database, and the data was once again sorted based on the relative amount of existing and runway aluminum in each landfill. In addition, the runway amount of aluminum landfilled by each organization in each Texas county was calculated and sorted. Republic Services Inc. owns 2 landfills within Harris County in Texas that could potentially contain the most aluminum, at 2.33 Mt by the year 2050, as compared to other organizations in any other Texas county.

$$Watse\ Rate\ \left(\frac{Mt}{year}\right) = \frac{Waste\ in\ Place\ (tons)}{(Closure\ Year\ 0r\ 2020) - Opening\ Year} \quad \text{[Equation 1]}$$

$$Relative\ \text{Runway}\ Al.\ (Mt) = (Waste\ in\ Place\ (Mt) + (Waste\ Rate\ \left(\frac{Mt}{year}\right) * (Closure\ Year - Waste\ in\ Place\ Year))) * 0.018 \quad \text{[Equation 2]}$$

Table 2.3. Sample of Texas EPA LMOP Landfill Database Sorted by Relative Projected Runway Amount of Aluminum by Organization and County. Color coordinated with orange indicating county sorting and green representing the organization. Data for waste in place most recently from 2020.

Landfill Name	City	County	Ownership Type	LF Owner Org.(s)	Year Open	Year Close	Waste in Place (Mt)	Relative Runway Al (Mt)	Relative Al (Mt)	Sum of Runway Al/LF Org. by County (Mt)
Whispering Pines LF	Houston	Harris	Private	Republic Services, Inc.	1978	2044	9.30	0.26	0.17	2.33
McCarty Road LF	Houston	Harris	Private	Republic Services, Inc.	1972	2033	90.33	2.07	1.63	2.33
McCommas Bluff LF	Dallas	Dallas	Public	City of Dallas, TX	1981	2050*	50.21	1.60	0.90	1.60
Covel Gardens RDF	San Antonio	Bexar	Private	Waste Management, Inc.	1993	2050*	33.04	1.26	0.59	1.26
DFW Recycling & Disposal Facility	Lewisville	Denton	Private	Waste Management, Inc.	1972	2023	64.99	1.24	1.17	1.24
Atascocita RDF	Humble	Harris	Private	Waste Management, Inc.	1983	2041	35.42	1.00	0.64	1.04
Blue Bonnet LF	Houston	Harris	Private	Waste Management, Inc.	1979	1998	2.33	0.04	0.04	1.04
Tessman Road LF	San Antonio	Bexar	Private	Republic Services, Inc.	1982	2050*	31.61	1.02	0.57	1.02
Blue Ridge LF	Fresno	Fort Bend	Private	Republic Services, Inc.	1993	2050*	22.35	0.85	0.40	0.85
121 Regional Disposal Facility	Melissa	Collin	Public	North Texas Municipal Water District	2004	2050*	11.45	0.59	0.21	0.77
McKinney LF	McKinney	Collin	Public	North Texas Municipal Water District	1968	2008	5.93	0.11	0.11	0.77

Maxwell Creek LF	Wylie	Collin	Public	North Texas Municipal Water District	1982	2005	4.17	0.08	0.08	0.77

*Landfill closure years are capped in 2050 for more reasonable estimates of runway aluminum.

This study recognizes that the estimation of the runway amount of aluminum in each landfill does not consider the implementation of improved waste separation prior to landfilling, the increase demand for aluminum products that would in turn likely increase the amount of aluminum landfilled, or a nonlinear rate of aluminum being landfilled over time. This rough estimation was only utilized to identify organizations and counties that may be able to have a LFMR project, and the runway values estimated are not utilized specifically for any further calculation.

2.1.3 Texas Landfill Database

Based on literature review of previous landfill mining projects attempted in Texas (Zakira 2017 and Houston One Voice 2022), the identification of landfill mining permitting in Texas policy (TCEQ 2024a), and the promising estimations of aluminum in Texas landfills from the US EPA LMOP database, further investigation for potential landfill mining sites in Texas was pursued in this study. The Texas Commission on Environmental Quality (TCEQ) provides historical MSW landfill databases for permitted MSW landfill facilities that are open or closed, as well as closed and unnumbered landfills that operated prior to permitting requirements (TCEQ 2024b).

Similarly to the US EPA LMOP dataset, preliminary screening of the open, closed, and closed and unnumbered TCEQ datasets was completed. For the permitted landfill sites that are open and closed, duplicate data entries are removed in the same manner as completed for the US EPA LMOP datasets, in addition to transfer stations, and any landfill sites that received liquid waste, compost, or mulch. Landfill site locations that were labeled as probably or certainly hazardous, were not accepting household waste, and had an area of less than 6 acres were removed from the closed and unnumbered database for the purposes of this study. Landfill sites that were most likely accepting MSW and therefore aluminum were considered potential landfill mining sites and were included in the screened TCEQ databases for further analysis. The screened TCEQ data can be found in section A.4 of the Appendix.

The landfill databases accessed through the TCEQ are more comprehensive than the US EPA LMOP database for Texas, and therefore a comparison of the two databases was completed. The purpose of this comparison was to identify how inclusive the US EPA LMOP database may be for other states, as well as the extent of the overlap and a comparison of the data provided in the two different sets of data. A sample of landfills from each database was taken, chosen to be the landfills located in the 9 counties included in the Houston city limits: Austin, Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller. The Houston area was selected due to the previously estimated landfill aluminum content with the US EPA LMOP data, and the subset was required due to the TCEQ datasets being too large to screen manually in this study.

The results of this comparison can be found in detail in section A.5 of the Appendix. Table 2.4 below provides a summary categorized by the landfill type as defined by the TCEQ. A total of 123 landfills were defined in this combined database, and all 17 of the US EPA LMOP sites within the same counties are accounted for within the TCEQ landfill database. The permitted landfill mining site, type 9MR, is called the Ruffino Road Landfill and will be discussed more in the context of this study in the next section. The complete overlap of the US EPA LMOP and TCEQ databases indicates that the US EPA LMOP database could be utilized on the national scale for further site selection analysis, though the TCEQ database is more comprehensive. This indicates that the US EPA LMOP database would be a good starting point in landfill mining site selection analysis, but finer regional data should be utilized if possible.

Table 2.4. Summary of Combined US EPA LMOP and TCEQ Databases for Houston Counties. All 17 of the US EPA LMOP landfill sites in the same region are accounted for in the TCEQ database.

Landfill Type	Type Description	Count
Type 1	MSW	19
Type 2	Closed	3
Type 3	Upgraded	4
Type 4	Brush, construction, & demolition	28
Type 9MR	Landfill Mining, Permitted	1
CP	Construction over Closed MSW LFs, Permitted	3
CR	Construction over Closed MSW LFs, Registered	3
SUBT	Construction over Closed MSW LFs, Non-enclosed	9
UNUM	Closed, Operated before permits were required	53
	Total:	123

2.2 Ruffino Hills, Texas Case Study

In the state of Texas at the time of this study, a landfill mining permit was pending for the Ruffino Hills Landfill. The Ruffino Hills landfill had two periods of being an active MSW landfill between 1954 and 1988 for the city of Bellaire, and between 1959 and 1992 for the city of West University Place. The western half of the site is a 72.56-acre area owned by Bellaire, and the eastern 70.87 acres is owned by West University Place. After the closure of the landfills, a private golf course was built over them and was operational from 1994 to 2002 (Houston One Voice 2022). Aerial imagery of the Ruffino Hills site and its surroundings from before its use as a landfill, during, after as a golf course, and a more recent image post landfill and golf course closure can be seen in Figure 2.1 below. Most recently the site was used as a transfer station, though most of the area has remained vacant since the closure of the golf course.

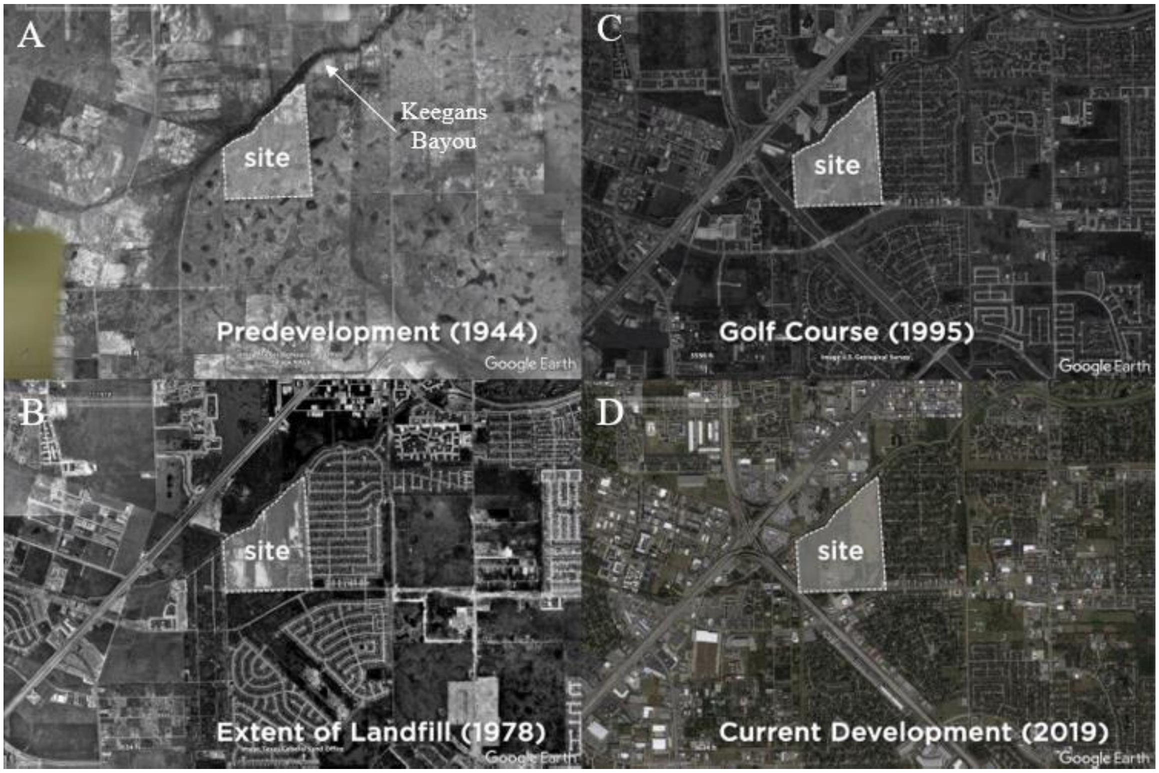

Figure 2.1. Historical Aerial Imagery of the Ruffino Hills Site. (A) Site prior to landfill activity and development in 1944 with note of Keegans Bayou location relative to landfill site. (B) Landfill site during operation and surrounding urban development in 1978. (C) Golf course development over closed landfill site in 1995. (D) Transfer station after golf course closure and recent surrounding urban development in 2019. (Houston One Voice 2022)

The proposed project at Ruffino Hills plans to utilize landfill mining as a method of purely removing the waste in place and trucking it to another location to allow space for beneficial community redevelopment and stormwater detention. The Ruffino Hills site lies directly South of Keegans Bayou, offering a unique opportunity for the Ruffino Hills landfill site to be utilized for stormwater detention (Figure 2.2) to reduce the extent and effects of flooding (Figure 2.3). In addition to the detention area proposed at the Ruffino Hills site, two other small detention areas upstream from the Ruffino Hills landfill site are proposed in Figure 2.2 by the City of Houston. The yellow and red areas in Figure 2.3 represent partial and greater reductions respectively to flood hazard within the Keegans Bayou watershed. Light blue shading in the same figure represents the extent of a 100-year precipitation event, or an event with a 1% chance of annual occurrence. Along with the improved stormwater management, the proposed plan for the Ruffino Hills landfill site includes a community-based development to encourage economic stability and growth, as well as the creation of natural green spaces as parks (Houston One Voice 2022).

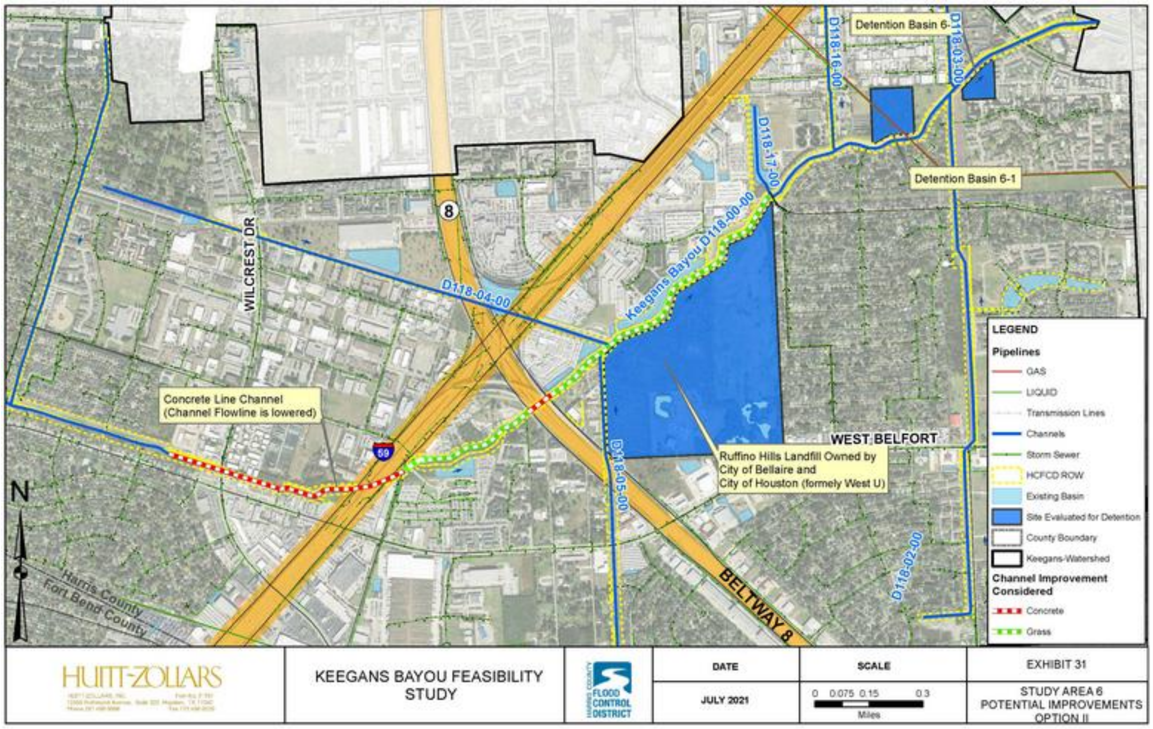

Figure 2.2. Keegans Bayou Areas with Potential for Detention Improvement (Houston Public Works 2023).

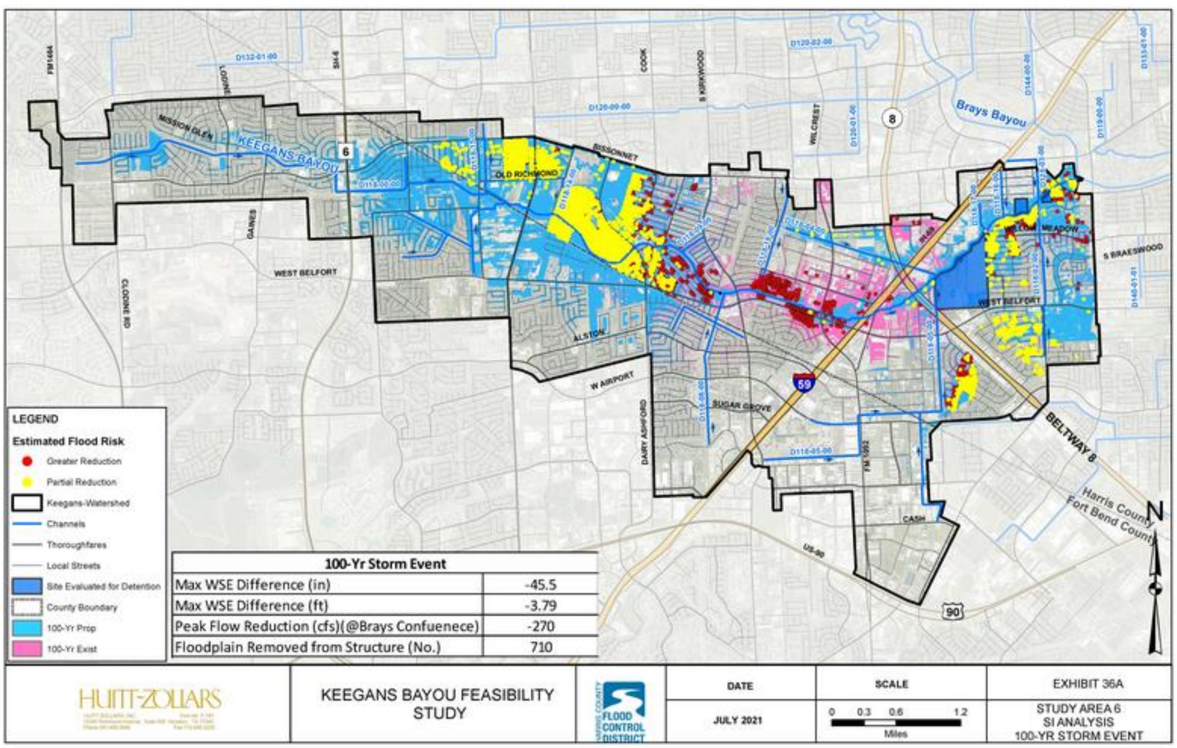

Figure 2.3. Keegans Bayou with 100-yr Storm Event and Improvements from Added Detention. Yellow and red areas indicate partial and greater flood risk reduction due to added detention area. (Houston Public Works 2023)

The proposed project for utilizing the closed Ruffino Hills landfill site in Houston, Texas does not currently include sorting or recycling any of the mined landfilled waste, only relocating it. Implementing a step in the mining of landfilled waste where any recyclable material can be sorted from organic and unusable material has both environmental and economic benefits. The proposed Ruffino Hills detention project highlights the importance of identifying co-benefits that make landfill mining more economically, environmentally, and socially viable and desirable for communities to employ. The major incentive for the City of Houston to purchase the Ruffino Hills site was its location relative to Keegans Bayou and the opportunity to excavate, or mine, the waste in the landfill to create a stormwater detention space to mitigate flood risk in the area. Other economic and community benefits such as office space, sports facilities, recreational green space, and other business space surrounding the detention structures are also included in the Ruffino Hills proposal. The co-benefits described in the project proposal for Ruffino Hills (Houston One Voice 2022) provide inspiration for further site selection criteria in this study.

2.3 ArcGIS Analysis

2.3.1 Houston Landfill Mapping

To visualize the spatial distribution of the landfill sites in the 9 counties included in Houston, all US EPA LMOP, and TCEQ open, closed, and closed and unnumbered landfill sites compiled previously for the City of Houston were mapped in ArcGIS (Figure 2.4). In ArcGIS each site was denoted by the site's physical type as defined previously (Table 2.4). A total of 123 landfill sites were identified in the US EPA LMOP and TCEQ combined database and can be seen in Figure 2.4 below. From the spatial distribution observed by mapping the landfill site for the Houston area, it can be generalized that a majority of the closed and unnumbered landfill sites are clustered near the city center, while the larger, open MSW landfill sites are further from the current city center. It was assumed in this study that as the population and urban sprawl of the city grew, the demand for greater landfill space increased. Landfill site locations are typically further from densely populated areas, matching the observed trend of the open, MSW landfills primarily lying further from the city center. The smaller, closed and unnumbered landfill sites were eventually overtaken by the rapid urbanization of the City of Houston and repurposed for various redevelopment projects.

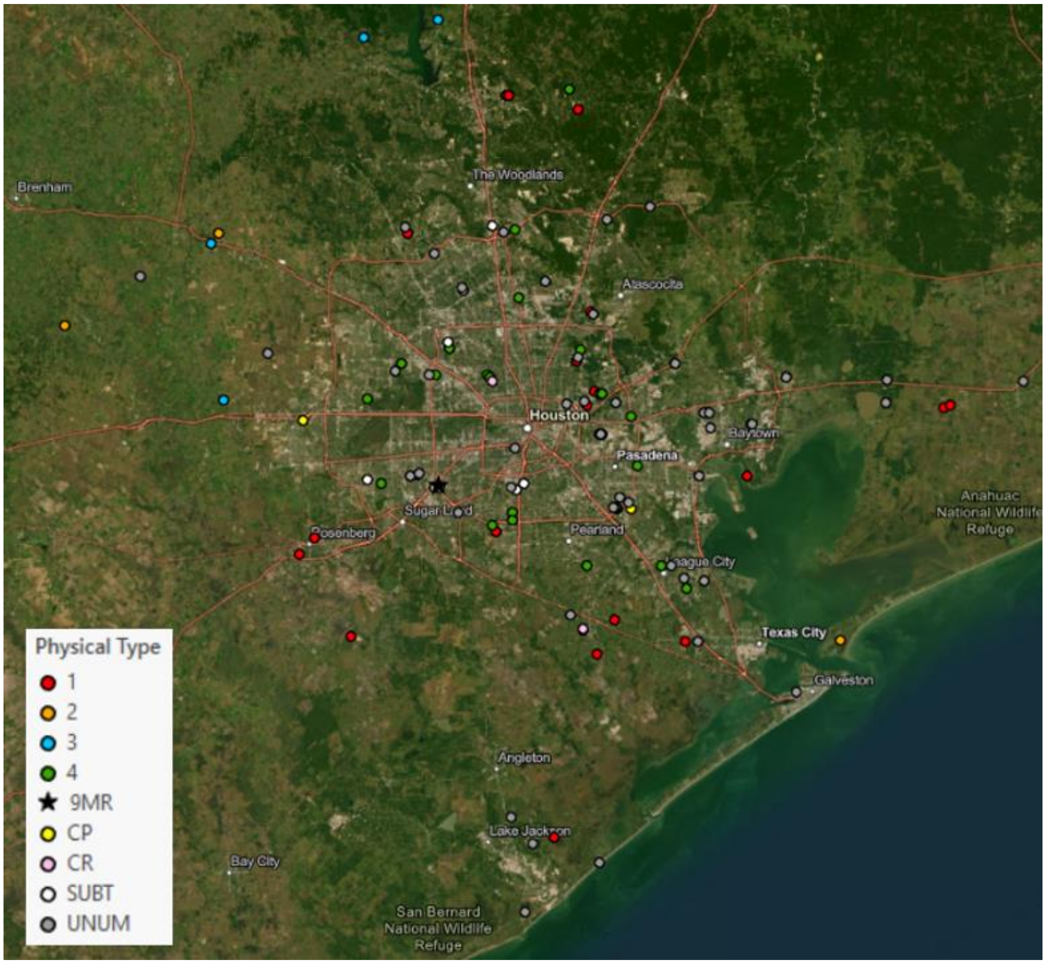

Figure 2.4. ArcGIS Mapping of Landfills in Houston, TX. Ruffino Hills landfill site is denoted with a black star.

Once mapped in ArcGIS, the classification of each landfill type, as well as any other structures or conditions of note, can be confirmed with available satellite imagery. The satellite imagery can reveal closed landfills that have already been redeveloped and are likely no longer available to landfill mining. Factors such proximity to highly populated areas or communities, water bodies, and the general distribution of landfills across this sampled area are kept in mind while landfill sites are observed manually. In this study, 54 of the 123 landfill sites from the compiled US EPA LMOP and TCEQ database were reviewed in this manner.

Some examples from the review of 54 of 123 landfill sites from the compiled database created previously with their most recent satellite imagery are found in the figures below. The Addicks Fairbanks Landfill is shown in Figure 2.5, which is a type 4 landfill, or a landfill that accepted brush, construction, and demolition waste. The Addicks Fairbanks landfill has been closed and capped, and permitting regarding the landfill has been completed post-closure. Based on the recent satellite imagery, this landfill has not been redeveloped since it has been capped. There appears to be residential areas southwest of the landfill, and industrial activity east of the landfill. Additionally, Horsepen Creek directly borders the landfill to the west.

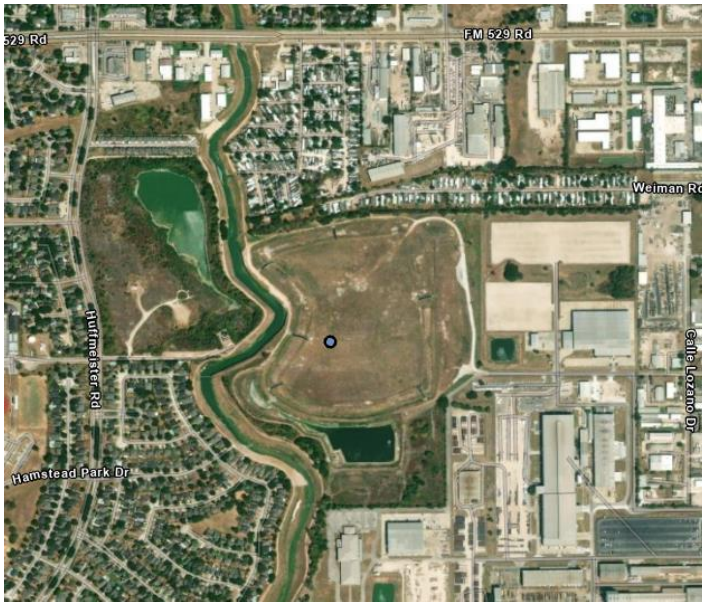

Figure 2.5. Satellite Imagery of the Addicks Fairbanks Landfill. Horsepen Creek lies directly west of the landfill site.

Similar to the proposed Ruffino Hills project, the proximity of the Addicks Fairbanks Landfill to Horsepen Creek could allow for a similar co-benefit of stormwater detention and flood mitigation with landfill mining for the purpose of recyclable material recovery. The feasibility of landfill mining at this site would depend on identifying measurable benefit to flood mitigation and bore hole testing to estimate the contents of the landfill. Considering community input and the risks and benefits associated with a landfill mining project at this location would also be an important step.

In Figure 2.6, the sites of the Olshan Demolishing Landfill and the Doty Sand Pit Venture Landfill can be viewed. The Olshan Demolishing landfill is a SUBT type landfill, or there has been construction over a closed MSW landfill that has not been enclosed. The Doty Sand Pit Venture Landfill is a closed type 4 landfill, or a landfill that accepted brush, construction, and demolition waste. The Doty Sand Pit Venture landfill was registered as closed in January of 2001, and the Olshan Demolishing landfill was a smaller operation closed before that date. After the closure of the Doty Sand Pit Venture, a golf course was built on the site. In 2005, a developer proposed a 730-unit subdivision plan over the closed landfills. This project did not take place due to community backlash based on historical methane gas leakage from the landfill (Chron News 2005).

Figure 2.6. Satellite Imagery of the Olshan Demolishing Landfill and the Doty Sand Pit Venture Landfill. The Olshan Demolishing landfill is denoted by the orange point in the northeast of the site, and the Doty Sand Pit Venture landfill is denoted in brown and represents most of the total site area.

The combined site with the Olshan Demolishing landfill and the Doty Sand Pit Venture landfill experienced a failed attempt for redevelopment in the past. While monitoring and controlled venting of the landfill methane gas was required by the TCEQ and completed, this large site remains undeveloped or reused at the time of this study. The potential for methane gas capture for energy production and greenhouse gas emission reduction could be useful for this site, though LFG collection systems must be undisturbed making a concurrent landfill mining project impossible. These two different types of projects, being LFG collection and landfill mining, could occur sequentially as co-benefits if adequate analysis of the environmental and economic benefits of each project type were balanced and maximized.

In Figure 2.7, aerial satellite imagery of the 31-acre Harris Landfill site can be viewed. This landfill is a closed, unnumbered landfill, indicating that it was operated prior to landfill permitting requirements being in place through the TCEQ. This site was formerly owned by the Creekside Sand & Gravel Company, and the C.C. Murray landfill operators. Historical records from the TCEQ indicate that the Harris Landfill was primarily type 4, or a landfill that accepted brush, construction, and demolition waste. The landfill was closed prior to the 1990’s, deemed non-hazardous by the TCEQ, and has since been reused as a golf driving range, and most recently as a sports center with soccer fields.

Figure 2.7. Satellite Imagery of the Harris Landfill.

Landfill sites such as Harris landfill offer an example of how closed landfill space has been utilized to provide community or economic benefit. The potential benefits for a community to utilize LFMR on a site like Harris landfill may be less successful with its current area already having been redeveloped. Further research regarding the specific contents of the landfill, community needs and priorities, and identification of other potential co-benefits to utilize LFMR would be necessary at this site.

The manual screening of 54 of the 123 landfill sites from the US EPA LMOP and TCEQ compiled database was time consuming and inefficient. Similar analysis at a larger scale with a greater number of landfill sites would require an automated process. An automated process is not investigated in this study, though it is recognized that the potential for utilizing ArcGIS software and additional data sets with defined variables that would differentiate various redevelopment features could be possible. For example, land use and landcover datasets could be added to the ArcGIS maps in this study to additionally screen different overlaps with landfill site locations as a measure of current site status and use.

2.3.2 Houston Landfill and Floodplain Mapping

As previously identified in the proposed Ruffino Hills detention project, stormwater mitigation could be used as a viable co-benefit for identifying potential landfill mining sites. Federal Emergency Management Agency (FEMA) flood hazard maps are included in the ArcGIS map of the compiled Houston landfill sites. A tool to find intersections between the FEMA regulated floodplains and the Houston landfill sites is utilized. However, this method did not capture the Ruffino Hills landfill due to the recognized coordinates lying outside of the floodplain. The available data in this study includes coordinate points rather than the entire area of a landfill's extent. To capture more sites, another tool to record intersections from a designated radius about a coordinate is utilized flagging additional sites in the Houston area.

The scope of this study does not specifically address changes in elevation related to landfill construction and design. It is recognized by this study that the FEMA regulated floodplain data inherently includes a factor of elevation considerations, but the elevation in which waste has been placed in landfill sites is not investigated. The potential mining of landfill sites for the purposes of flood hazard mitigation would require more detailed research regarding the waste depth relative to storm flood depths to justify the environmental and economic benefits of landfill mining to create detention basins.

In Figure 2.6 below, the same landfill layer based on the compiled Houston LMOP and TCEQ data is shown along with the FEMA flood hazard layer (FEMA 2024). The FEMA flood hazard layer includes the 0.2% annual chance flood hazard, or the 500-year flood event, the 1% annual chance flood hazard, or the 100-year event, along with the regulatory floodways, areas of future 1% annual chance flood hazard risk, and areas that have a reduced risk to flood due to levees. Overlap of the landfill site location data with any of these regions quantified in the FEMA flood hazard map have the potential for utilizing stormwater mitigation or flood detention as a co-benefit to landfill mining like the Ruffino Hills landfill project does.

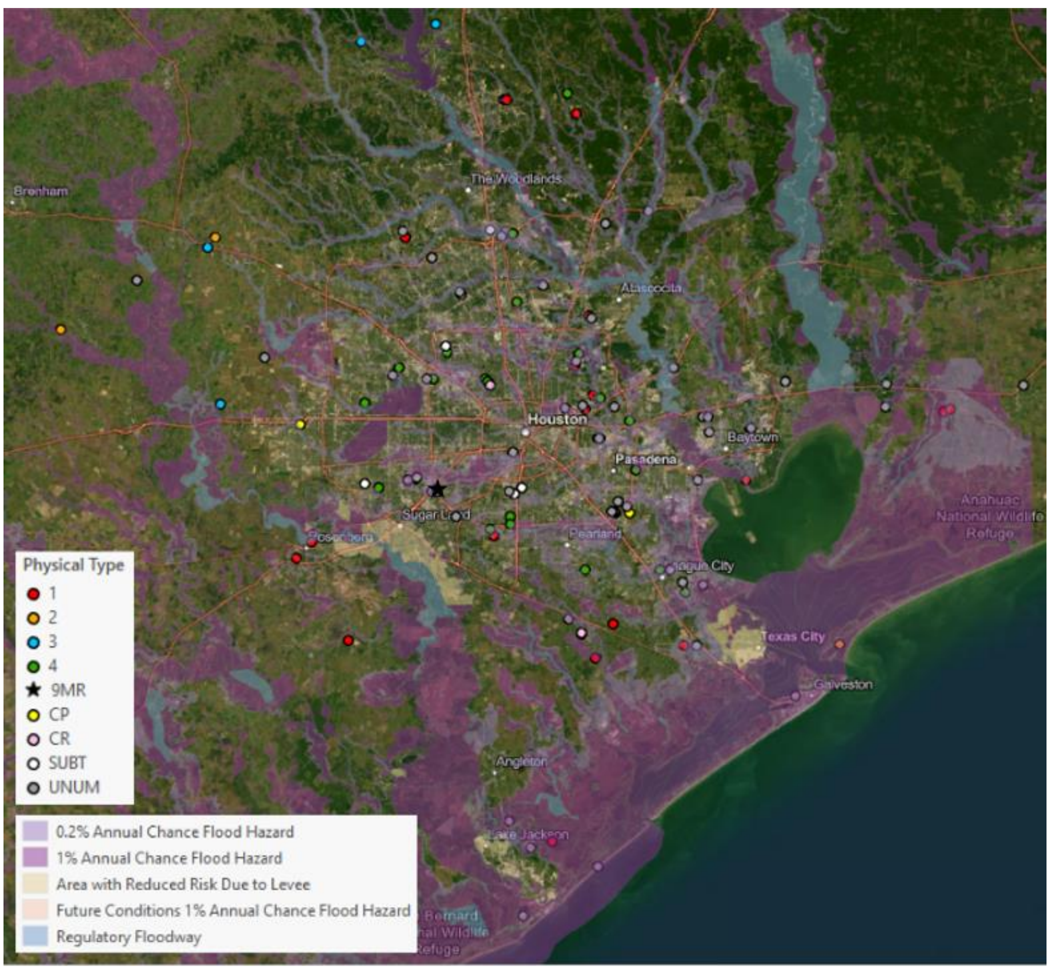

Figure 2.8. ArcGIS Mapping of Landfills and FEMA Flood Hazard in Houston, TX. Ruffino Hills landfill site is denoted with a black star.

The intersect tool in ArcGIS identifies the overlap of the landfill sites based on their coordinates and the extent of the FEMA flood risk area. The results of the intersect function are summarized in Table 2.5 below. As a check for this approach, the Ruffino Hills site is utilized. The intersect tool did not return the Ruffino Hills landfill as overlapping with the FEMA flood risk map, contradicting the previous case study's identification of flood detention as being a strong co-benefit to their project. Figure 2.7 shows the coordinates mapped for both the Bellaire and West University Landfills, both of which do not overlap with the FEMA flood hazard map. Without detailed data for landfill areas, an approximation to attempt to account for the actual overlap of landfill area not included in the coordinates is completed with the summarize nearby tool in ArcGIS. This tool creates a radius of a defined distance about a point and then completes the same type of overlap analysis with another feature layer, in this case, the FEMA flood hazard map. A radius of 0.5 kilometers is chosen as the radius about the landfill coordinates, and a new analysis comparing landfill location and the FEMA flood hazard is completed. The results of the summarize nearby tool in ArcGIS can be found in Table 2.6 below.

Table 2.5. ArcGIS Intersect Results between Compiled US EPA LMOP and TCEQ Data and FEMA Flood Hazard Map. Total Landfill Sites sampled, 123.

Type	**Count**	**Type**	**Count**
1	8	Active	13
2	1	Not Constructed	2
4	9	Closed	4
SUBT	2	Closed UNUM	25
UNUM	25	Post Closure	1
Total:	**45**	**Total:**	**45**

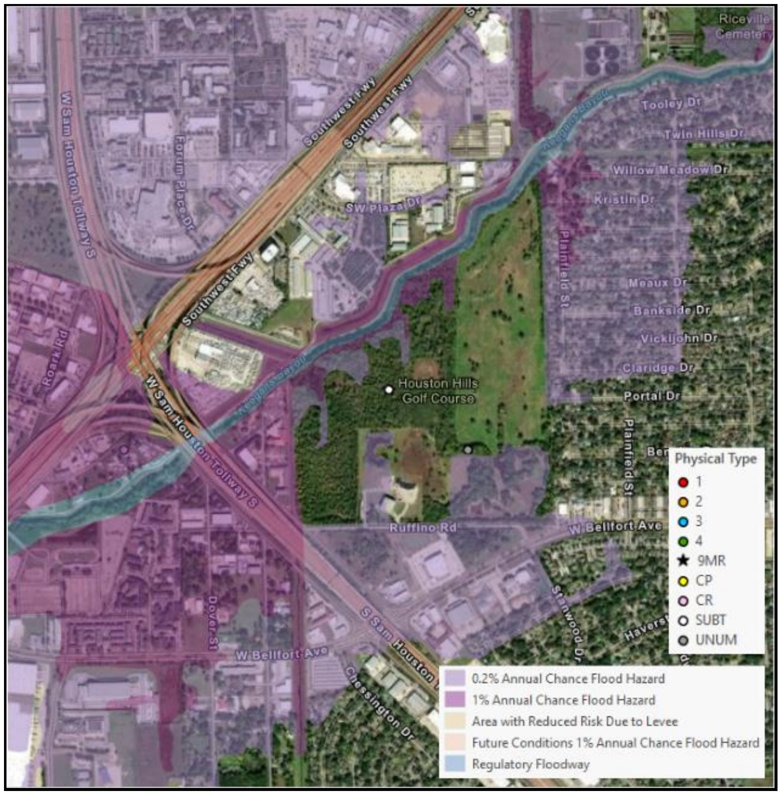

Figure 2.9. Ruffino Hills Site Including Bellaire and West University Landfills and FEMA Flood Hazard Map.

Table 2.6. ArcGIS Summarize Nearby with 0.5km Radius Results between Compiled US EPA LMOP and TCEQ Data and FEMA Flood Hazard Map. Total Landfill Sites sampled, 123.

Type	Count	Type	Count
1	17	Active	23
2	2	Not Constructed	6
4	20	Closed	16
9MR	1	Closed UNUM	40
CP	1	Post Closure	6
CR	1	**Total:**	**91**
SUBT	6		
UNUM	40		
Total:	**91**		

The summarize nearby tool in ArcGIS identified an additional 46 landfills within 0.5 kilometers of the FEMA flood hazard map. Of the 123 landfills considered in the Houston, Texas area there are 91 landfill sites identified as potentially being impacted by flood conditions. The Ruffino Hills site can once again be seen in Figure 2.7 below, and the black circles around both the Bellaire and West University indicate the 0.5-kilometer radius about each site utilized by the summarize nearby tool in ArcGIS.

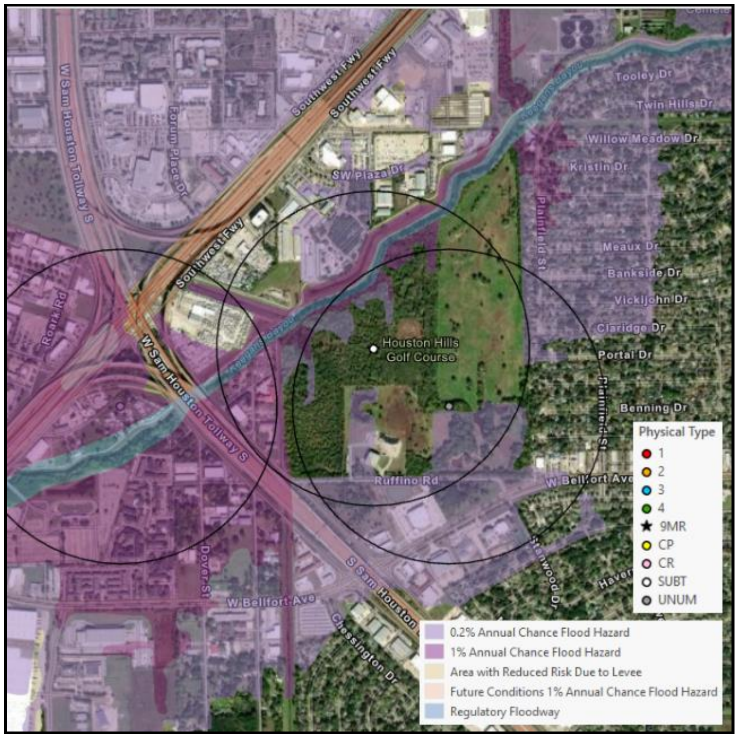

Figure 2.10. Ruffino Hills Site Including Bellaire and West University Landfills and Summarize Nearby with FEMA Flood Hazard Map. The two circles related to the West University Place and Bellaire landfill sites associated with the Ruffino Hills site are on the right of the figure, and an additional closed and unnumbered landfill site lies to the left of the figure.

The location of Houston, Texas along the Gulf Coast with frequent tropical storms and hurricanes as well as the rapid growth and unplanned urban sprawl are both major contributors to the city’s high flood risk. In 2016, the population of Houston was 6,772,852 and the projected 2040 population is expected to exceed 10 million. The urbanization associated with the anticipated growing population along with rapid growth in the past (Figure 2.11) has led to unplanned and excessive urbanization and impervious surface. The loss of 30% of Houston’s freshwater wetlands to the impervious surface area increases flood risk by creating stormwater responses over the land surface that are more intense and of higher velocities. These conditions lead to greater stormwater runoff volumes that can be damaging. Wetlands are natural detention areas that slow the flow of water over the land surface, in addition to improving water quality and providing habitats for more biodiverse ecosystems. However, wetlands are typically considered land with low economic value. The management for the urban growth in Houston has been market driven rather than environmentally focused, exacerbating the flood risks across the city. The effects of climate change will only increase the frequency and intensity of precipitation events. (Berke 2017)

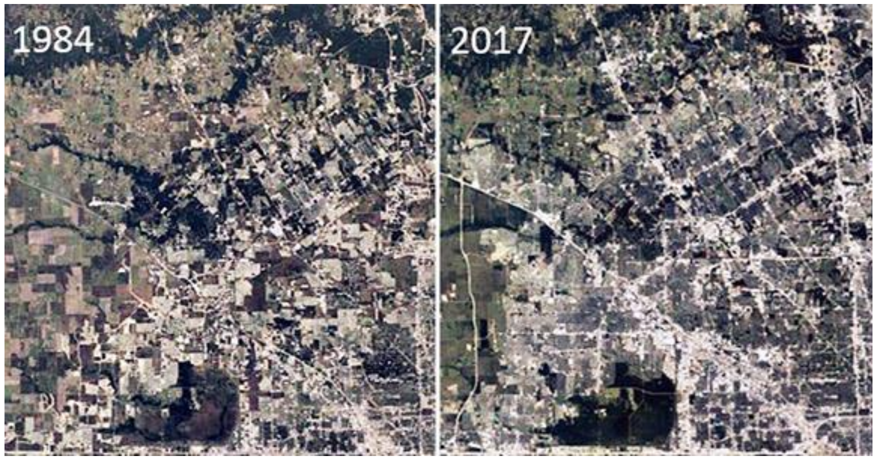

Figure 2.11. Houston Satellite Imagery in 1984 and 2017. Increased impervious area and urban sprawl in 2017 ariel image versus in 1984. (Berke 2017)

The consideration of landfill mining operations within a flood hazard area was recognized by the study. There are assumed environmental and social risks associated with an excavated landfill site experiencing a storm event or flood. The short-term risks of excavating a landfill site in a flood hazard area must be weighed against the benefits of improved flood mitigation upon completion of a project. Further considerations of this regard are not completed at the time of this study but are suggested for future work.

The combination of the previously identified potential for Houston landfills to contain some of the greatest amounts of aluminum of all landfills across the state of Texas, and the dire need for flooding solutions in the city could result in more landfill mining projects like the Ruffino Hills case to arise. While flood mitigation through the construction of a detention basin in the proposed Ruffino Hills project was a major factor in justifying the projects feasibility, additional co-benefits for the community are also suggested, including office or business space and community green space. The proposal of final redevelopment projects that can fulfill multiple needs of a community could provide a better use of limited space and have an improved chance of feasibility.

2.3.3 United States Landfill and Floodplain Mapping

The success and proof of concept in automating results in ArcGIS for the Houston area for the intersection and proximity of landfills to the FEMA flood hazard map predict that the study area can increase to the entire US. The TCEQ dataset was more comprehensive than the US EPA LMOP dataset, however all the Houston area sites in the US EPA LMOP dataset were included in the TCEQ dataset for the same area. Therefore, it can be reasonably assumed that utilizing the US EPA LMOP database for a nationwide analysis of intersection and proximity between landfill sites and flood hazard area would be appropriate (Figure 2.9). At the time of this study, access to the entirety of the FEMA flood hazard map is limited, and the same analyses completed for the Houston area are not possible without full access to the FEMA data. It is the recommendation of this study that the same process completed in Houston is repeated with these nationwide datasets to identify more potential landfill mining sites that could utilize stormwater mitigation or flood detention as a co-benefit.

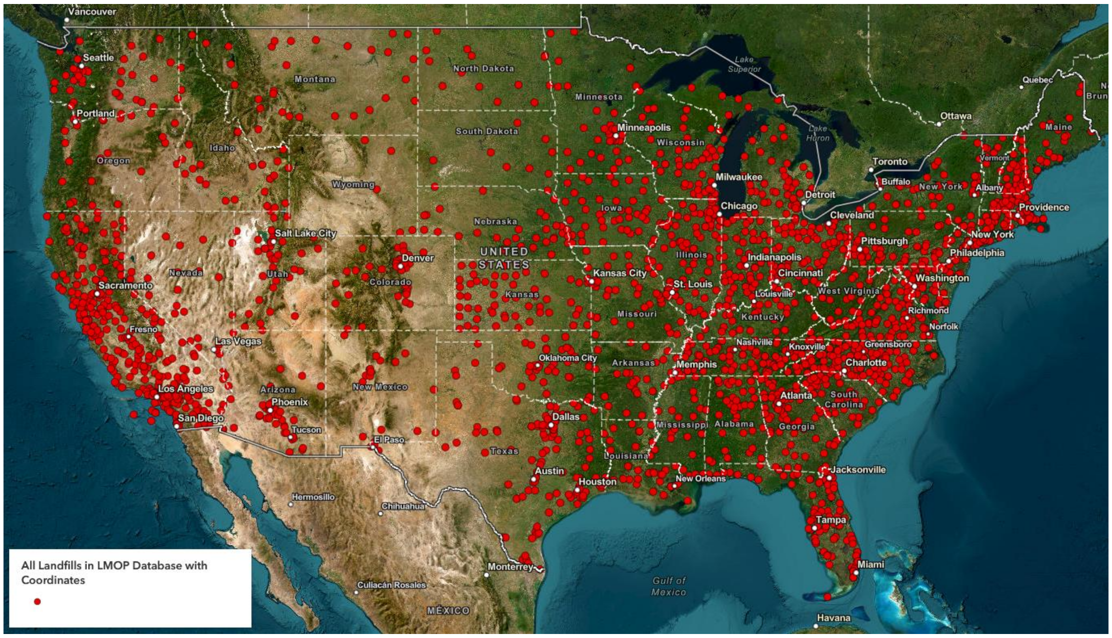

Figure 2.12. US EPA LMOP Nationwide Map.

2.4 Additional Co-Benefits and Environmental Justice

Inclusion of environmental justice and the consideration of social science is suggested to be prioritized by this study when identifying potential landfill mining project sites. The potential for mitigating environmental risks through landfill mining may not outweigh the risks created by excavating potentially harmful waste. The positive outcomes from landfill mining, and particularly ELFM, could be the creation of jobs for a community, development of facilities or businesses that directly benefit the community such as green space, community centers, sports centers, office space, or small business fronts. From an environmental perspective, the energy and material extraction from landfills can be a great economic stimulant for a community and could occur in conjunction with the previously mentioned improvements of landfill spaces.

A preliminary effort to visualize other co-benefits other than flood risk, other environmental justice and socioeconomic indicators are mapped with the landfill location databases created previously in this study (EPA EJScreen 2024). This includes proximity to hazardous waste, airborne pollutants, race and ethnicity demographics, and economic class. Some examples can be viewed below in Figures 2.13 and 2.14. Figure 2.13 provides the EPA EJScreen socioeconomic indicator for national percentiles for populations of people of color and the previously compiled landfill database for Houston, Texas. Generally, overlap and correlation between areas with greater populations of people of color and landfill sites is observed. In Figure 2.14, the national percentile for low-income populations and the same landfill database are mapped. There appears to be a general correlation between higher densities of low-income populations and landfill sites observed. As stated previously, the relative importance of these indicators and their link to solutions that could be co-benefits in a landfill mining project is unknown without further community input and collaboration. This study does not include further community outreach and research, though interviews and review of community needs are recommended as a future next step in this study.

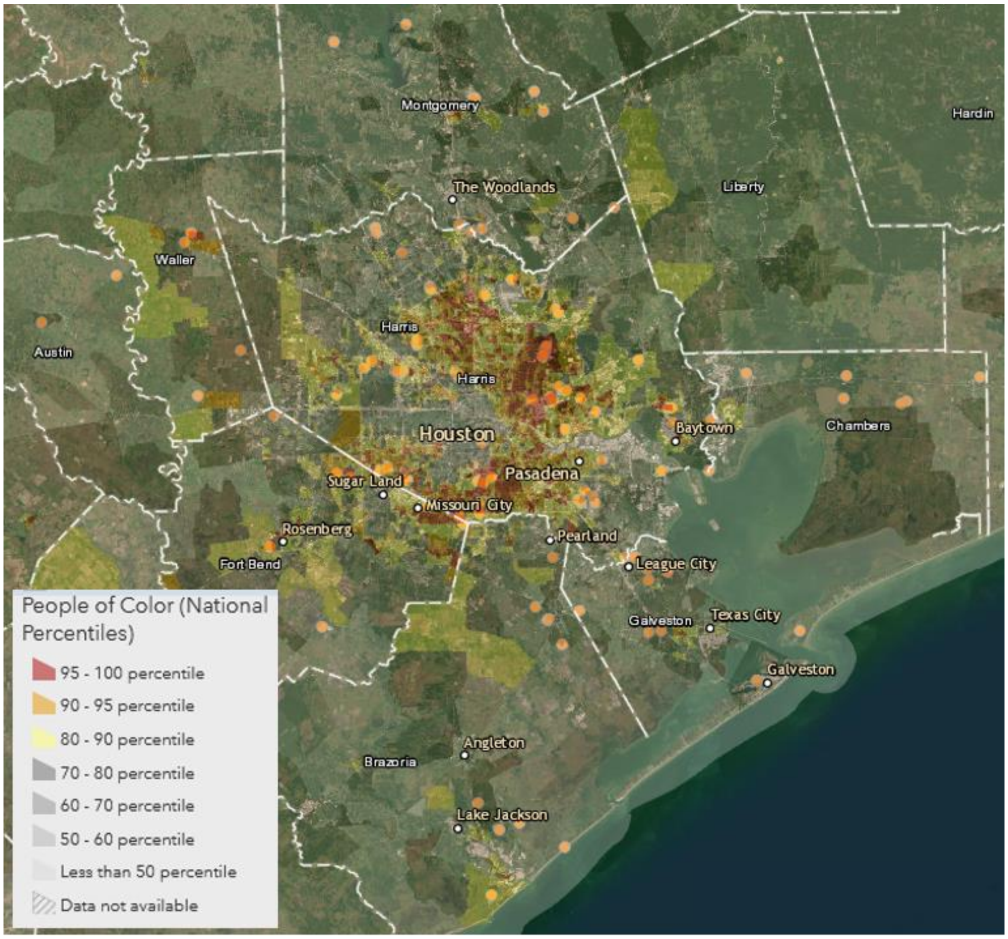

Figure 2.13. EJScreen Mapping of People of Color Demographics and Landfills for Houston, TX. 123 Landfill site locations shown in orange from the TCEQ and US EPA LMOP database compilation and national percentiles for populations of people of color. (EPA EJScreen 2024)

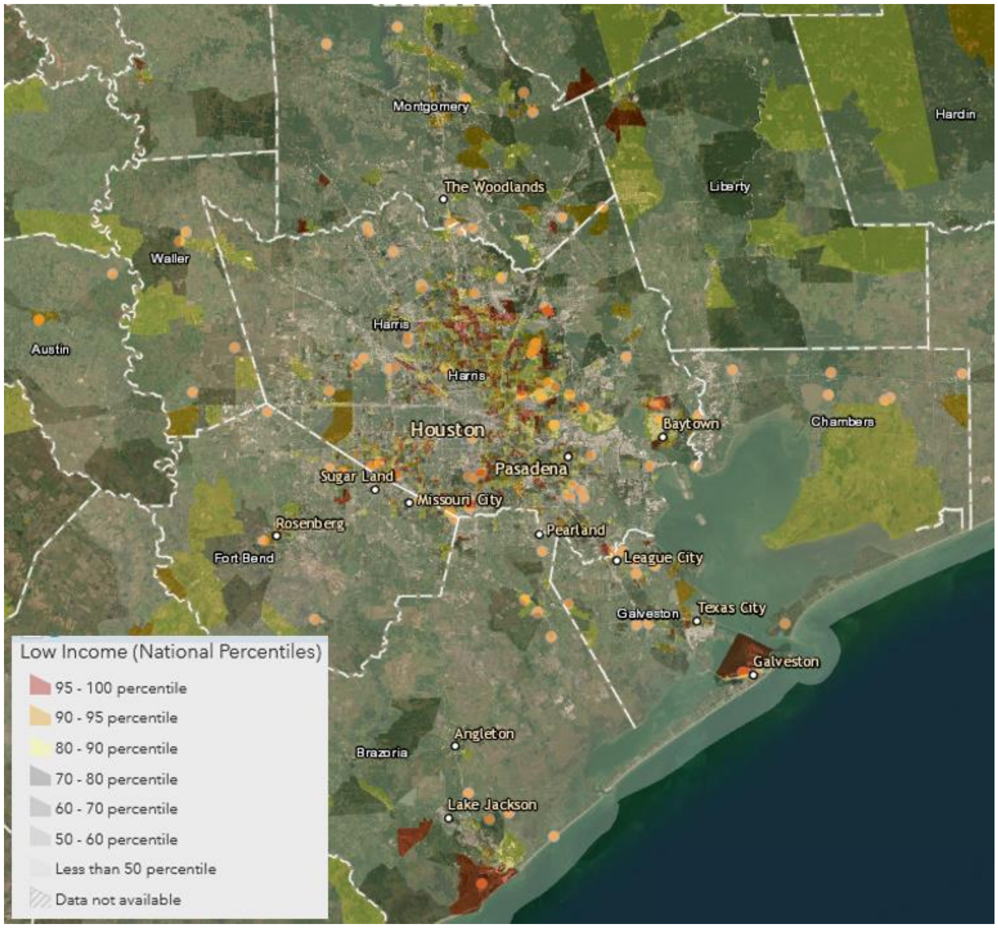

Figure 2.14. EJScreen Mapping of Low-Income Populations and Landfills for Houston, TX. 123 Landfill site locations shown in orange from the TCEQ and US EPA LMOP database compilation and national percentiles for low-income populations. (EPA EJScreen 2024)

3 Conclusions

As stated previously, the US does not currently have its own bauxite mines to contribute to viable primary aluminum production. The production of secondary aluminum in the US is an established process, and therefore the extraction and processing of bauxite may not be the most sustainable for the future of the nation. The potential for aluminum mining from landfills to produce more secondary aluminum in the US is a viable solution in response to the projected increase in global aluminum demand and avoidance of harmful environmental emissions associated with primary aluminum production.

This study also highlights the importance of valuing community input and needs as co-benefits that can make landfill mining projects economically viable and desirable. The databases in this study that are analyzed and sorted are useful tools in identifying potential landfill mining project sites. The Ruffino Hills case study in Houston, Texas reinforces the potential of landfill mining in the state due to the lack of a bottle bill, specific landfill mining permitting, and historical aluminum can disposal rates. The ArcGIS analysis completed in this study provides preliminary information regarding landfill mining site selection according to flood hazard proximity and development status determined through satellite imagery. Successful automation of these analyses for statewide or national scales has not yet been achieved and is recommended as a future research opportunity. Further research including bore hole testing to estimate the amount of aluminum in landfills is recommended. The future of material production will trend towards the reuse and recycling of products, and this study provides a preliminary approach to assessing the feasibility of landfill mining to recover aluminum through an interdisciplinary approach.

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A Appendix

A.1 Aluminum Production and Disposal in the US

During the review and analysis of aluminum production and disposal in the US, the breakdown by weight and percentage by weight of landfilled MSW was reviewed on a nationwide scale (US EPA 2020). The percentage by weight of MSW landfilled that was aluminum is utilized further in calculations in this study for estimating site specific aluminum content.

Table A.1. Materials Landfilled in the Municipal Waste Stream from 1960 to 2018. Landfilling after recycling, composting, other food management pathways and combustion with energy recovery. Does not include construction & demolition debris, industrial process wastes or certain other wastes. (US EPA 2020)

Materials	Thousands of Tons									
	1960	1970	1980	1990	2000	2005	2010	2015	2017	2018
Paper and Paperboard	24,910	37,390	42,560	43,570	40,450	35,080	22,000	18,280	18,350	17,220
Glass	6,620	12,520	14,080	8,660	8,100	8,290	7,030	6,840	7,580	7,550
Metals										
Ferrous	10,250	12,150	12,000	8,720	7,860	8,550	9,310	9,970	10,430	10,530
Aluminum	340	790	1,390	1,500	1,940	2,230	2,390	2,490	2,670	2,660
Other Nonferrous	180	350	600	310	490	530	520	660	730	740
Total Metals	*10,770*	*13,290*	*13,990*	*10,530*	*10,290*	*11,310*	*12,220*	*13,120*	*13,830*	*13,930*
Plastics	390	2,900	6,670	13,780	19,950	23,270	24,370	26,030	26,820	26,970
Rubber and Leather	1,510	2,710	4,000	4,590	3,880	4,130	4,400	4,490	4,950	4,990
Textiles	1,710	1,970	2,320	4,270	6,280	7,570	8,900	10,540	11,150	11,300
Wood	3,030	3,710	6,860	10,000	9,910	10,690	11,120	11,070	12,290	12,150
Other **	70	470	1,990	2,100	2,480	2,570	2,800	2,980	2,970	2,930
Total Materials in Products	***49,010***	***74,960***	***92,470***	***97,500***	***101,340***	***102,910***	***92,840***	***93,350***	***97,940***	***97,040***
Other Wastes										
Food	12,200	12,750	12,740	19,800	24,200	26,370	28,620	30,250	30,630	35,280
Yard Trimmings	20,000	23,110	26,950	25,560	11,900	9,990	11,690	10,800	8,650	10,530
Miscellaneous Inorganic Wastes	1,300	1,770	2,200	2,410	2,820	3,020	3,160	3,210	3,250	3,270
Total Other Wastes	***33,500***	***37,630***	***41,890***	***47,770***	***38,920***	***39,380***	***43,470***	***44,260***	***42,530***	***49,080***
Total MSW Landfilled - Weight	***82,510***	***112,590***	***134,360***	***145,270***	***140,260***	***142,290***	***136,310***	***137,610***	***140,470***	***146,120***
Materials	**Percent of Total Landfilled**									
	1960	1970	1980	1990	2000	2005	2010	2015	2017	2018
Paper and Paperboard	30.2%	33.2%	31.7%	30.0%	28.8%	24.7%	16.1%	13.3%	13.1%	11.8%
Glass	8.0%	11.1%	10.5%	6.0%	5.8%	5.8%	5.1%	5.0%	5.4%	5.2%
Metals										
Ferrous	12.4%	10.8%	8.9%	6.0%	5.6%	6.0%	6.8%	7.2%	7.4%	7.2%
Aluminum	0.4%	0.7%	1.0%	1.0%	1.4%	1.6%	1.8%	1.8%	1.9%	1.8%
Other Nonferrous	0.2%	0.3%	0.4%	0.2%	0.3%	0.3%	0.4%	0.5%	0.5%	0.5%
Total Metals	*13.0%*	*11.8%*	*10.3%*	*7.2%*	*7.3%*	*7.9%*	*9.0%*	*9.5%*	*9.8%*	*9.5%*
Plastics	0.5%	2.6%	5.0%	9.5%	14.2%	16.4%	17.9%	18.9%	19.1%	18.5%
Rubber and Leather	1.8%	2.4%	3.0%	3.2%	2.8%	2.9%	3.2%	3.3%	3.5%	3.4%
Textiles	2.1%	1.7%	1.7%	2.9%	4.5%	5.3%	6.5%	7.7%	7.9%	7.7%
Wood	3.7%	3.3%	5.1%	6.9%	7.1%	7.5%	8.2%	8.0%	8.7%	8.3%
Other **	0.1%	0.4%	1.5%	1.4%	1.8%	1.8%	2.1%	2.2%	2.2%	2.0%
Total Materials in Products	***59.4%***	***66.6%***	***68.8%***	***67.1%***	***72.3%***	***72.3%***	***68.1%***	***67.9%***	***69.7%***	***66.4%***
Other Wastes										
Food	14.8%	11.3%	9.5%	13.6%	17.3%	18.5%	21.0%	22.0%	21.8%	24.1%
Yard Trimmings	24.2%	20.5%	20.1%	17.6%	8.5%	7.0%	8.6%	7.8%	6.2%	7.2%
Miscellaneous Inorganic Wastes	1.6%	1.6%	1.6%	1.7%	1.9%	2.2%	2.3%	2.3%	2.3%	2.3%
Total Other Wastes	***40.6%***	***33.4%***	***31.2%***	***32.9%***	***27.7%***	***27.7%***	***31.9%***	***32.1%***	***30.3%***	***33.6%***
Total MSW Landfilled - %	***100.0%***	***100.0%***	***100.0%***	***100.0%***	***100.0%***	***100.0%***	***100.0%***	***100.0%***	***100.0%***	***100.0%***

A.2 Quantifying Landfilled Aluminum Databases

The nationwide recycling rates for each state can be found in Table A.2 below. This table also summarizes the status of bottle bills in each state and the year in which they were passed. Population data from April 2020 through July 2021 is also included in this table and is utilized in calculating the total weight of Al disposed, when multiplying the weight of aluminum per capita disposed by the given population. The column containing the estimated landfilled aluminum weight in thousands of metric tons for each state is sorted in descending order, and therefore the states with the greatest potential for aluminum found as used beverage containers (UBCs) in their landfills can be seen along the top rows of this table.

Table A.2. State Used Beverage Container (UBC) Statistics.

State	Al Can Recycling Rate (%)	Al Can Deposit	Year Bottle Bill was passed	Al kgs/ capita generated	Al kgs/ capita disposed	Al kgs/ capita recycled	Population (April 2020-July 2021)	Al disposed (Thousands of Metric Tons)
Texas	16	No		4.40	3.72	0.68	29,527,941	109.83
Florida	25	No		5.67	4.26	1.41	21,781,128	92.87
Illinois	24	No		4.85	3.67	1.18	12,671,469	46.56
Georgia	20	No		4.40	3.54	0.86	10,799,566	38.21
Ohio	16	No		3.81	3.22	0.59	11,780,017	37.94
California	78	Yes (CRV, 5c)	1987	3.63	0.82	2.81	39,237,836	32.04
North Carolina	16	No		3.36	2.81	0.54	10,551,162	29.67
New York	64	Yes (5c)	1983	3.81	1.36	2.45	19,835,913	26.99
New Jersey	60	No		7.30	2.90	4.40	9,267,130	26.90
Virginia	23	No		3.95	3.04	0.91	8,642,274	26.26
Pennsylvania	48	No		3.72	1.95	1.81	12,964,056	25.29
Indiana	17	No		4.13	3.40	0.68	6,805,985	23.15
Colorado	14	No		4.49	3.86	0.64	5,812,069	22.41
Tennessee	17	No		3.72	3.13	0.64	6,975,218	21.83
South Carolina	10	No		4.40	3.99	0.45	5,190,705	20.72
Missouri	18	No		3.90	3.18	0.73	6,168,187	19.58
Arizona	16	No		2.90	2.45	0.45	7,276,316	17.82
Wisconsin	27	No		4.13	2.99	1.09	5,895,908	17.65
Alabama	16	No		3.72	3.13	0.59	5,039,877	15.77
Louisiana	11	No		3.72	3.36	0.41	4,624,047	15.52
Maryland	54	No		5.49	2.49	2.99	6,165,129	15.38
Oklahoma	13	No		3.72	3.27	0.50	3,986,639	13.02
Kentucky	16	No		2.99	2.49	0.50	4,509,394	11.25
Washington	46	No		2.68	1.45	1.22	7,738,692	11.23
Utah	17	No		3.72	3.08	0.64	3,337,975	10.30
Nevada	15	No		3.72	3.18	0.54	3,143,991	9.98

Arkansas	12	No		3.72	3.27	0.45	3,025,891	9.88
Mississippi	12	No		3.72	3.27	0.45	2,949,965	9.63
Minnesota	43	No		2.77	1.59	1.22	5,707,390	9.06
Kansas	25	No		3.90	2.90	0.95	2,934,582	8.52
West Virginia	7	No		4.40	4.13	0.32	1,782,959	7.36
Massachusetts	70	Yes (5c)	1983	3.49	1.04	2.45	6,984,723	7.29
New Mexico	13	No		3.72	3.27	0.50	2,115,877	6.91
Nebraska	19	No		3.90	3.18	0.73	1,963,692	6.24
Idaho	17	No		3.72	3.13	0.64	1,900,923	5.95
Michigan	86	Yes (10c)	1978	4.13	0.59	3.54	10,050,811	5.93
Connecticut	61	Yes (5c)	1980	3.54	1.36	2.18	3,605,597	4.91
Iowa	76	Yes (5c)	1979	5.49	1.32	4.13	3,193,079	4.20
Montana	15	No		3.72	3.18	0.59	1,104,271	3.51
New Hampshire	32	No		3.54	2.45	1.13	1,388,992	3.40
South Dakota	25	No		3.90	2.95	0.95	895,376	2.64
Hawaii	61	Yes (5c)	2005	4.49	1.77	2.72	1,441,553	2.55
Alaska	3	No		3.49	3.40	0.09	732,673	2.49
Delaware	36	No		3.67	2.36	1.32	1,003,384	2.37
North Dakota	23	No		3.90	2.99	0.86	774,948	2.32
Oregon	85	Yes (10c)	1971	3.40	0.50	2.90	4,246,155	2.12
Wyoming	15	No		3.72	3.18	0.59	578,803	1.84
Rhode Island	39	No		2.27	1.41	0.91	1,095,610	1.54
Vermont	67	Yes (5c)	1973	5.08	1.68	3.40	645,570	1.08
Maine	85	Yes (5c)	1978	4.54	0.68	3.86	1,372,247	0.93

A.3 US EPA LMOP Databases

Attached below are the US EPA LMOP project site databases for Texas, Florida, Illinois, Georgia, Ohio, and California (US EPA 2024). These databases have each been sorted and ranked according to landfill sites estimated relative aluminum content by age, county, ownership, and potential future aluminum content.

Report Attachments\Texas Landfill Data with Sorting.xlsx
Report Attachments\Florida Landfill Data with Sorting.xlsx
Report Attachments\Illinois Landfill Data with Sorting.xlsx
Report Attachments\Georgia Landfill Data with Sorting.xlsx
Report Attachments\Ohio Landfill Data with Sorting.xlsx
Report Attachments\California Landfill Data with Sorting.xlsx

A.4 TCEQ Landfill Database

The TCEQ provides historical and current data of active, inactive, or pending permits, closed landfills, and closed and unnumbered MSW facilities in the state of Texas (TCEQ 2024b) and this data is attached below.

msw-facilities-texas-2.xls
msw-closed-facilities-texas-2.xls
msw-unum-texas-2.xlsx

A.5 US EPA LMOP and TCEQ Database Combination

The US EPA LMOP database and complete TCEQ database for landfill sites that lie within any of the 9 counties included in the Houston city limits: Austin Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller. Duplicates between the two sources are removed and a complied database is attached below.

Report Attachments\ArcGIS for all Houston Counties.xlsx